PATHOGENS AND PESTS OF CROPS

The literature contains a considerable amount of evidence of interactions between a) irrigation management and plant water status, and b) the spread and crop infestation of various plant pathogens (fungi, bacteria, viruses) and pests (mainly insects). For instance, as part of a series of books on "Plant water deficits and plant growth," Kozlowski (1978) published Volume 4 on the subject of "Water and plant diseases." This volume contains several relevant chapters by different authors, including: "Water stress as a pre-disposing factor in plant disease"; "Abiotic diseases induced by unfavorable water relations"; "Water and the infection process"; "Effect of soil moisture on survival and spread of pathogens." Agricultural water conservation actions, therefore, are likely to affect these interactions and thereby influence proliferation and infestation of pathogens and pests in irrigated agriculture.

Soil Preparation

Conserving water by improving its infiltration into the soil so as to curtail E_W because of ponding and E_S because of extended soil saturation, will reduce 1) the release of fungal zoospores (e.g., *Phytophthora* sp.) and 2) the distance travelled by the spores, resulting in less infestation by crop pathogens (Duniway, 1976). The practice of stubble planting with minimum tillage can improve the water holding capacity of the surface soil layers and reduce E_S because of the straw mulch, but that can also result in pathogen and pest buildup when straw and stubble are not burned. Lavee (1963) reported that mulching apple rootstock with wood shavings reduced soil temperature and thus enabled greater resistance to root-rot fungus. Toscano et al. (1979) found that reflective mulches (aluminum-coated paper or white polyethylene plastic) reduced aphid and virus infestation and improved the yield of summer squash by

45%. The mulching also promoted earlier harvest and thus reduced infection by late-season mosaic virus by 85%.

Skip-row planting of cotton can reduce the seasonal irrigation requirement. Ranney (1973) found that the skip-row areas of the field are equivalent to fallowing those areas, and that results in a lower infestation of verticillium wilt with consequent improvement in yield and quality of the cotton crop.

Irrigation Systems

Duniway (1977) cites several references (e.g., Cole et al., 1969; Cook and Papendick, 1972; Stolzy et al., 1965; Zimmer and Urie, 1967) which show that root and crown rots caused by Phytophthora spp. are usually associated with wet soil. A tailwater system reduces the chances of water accumulation at the lower ends of flood- or furrow-irrigated plots. Duniway (private communication) found that preventing this wet condition reduced infestation of pepper plants by Phytophthera spp.

By changing from over-tree to under-tree sprinkler systems in orchards evaporation and interception losses of water can be reduced. An incidental benefit of the change in system is a reduction in fungus and bacterial diseases of fruit trees, but there could also be an increase in mite damage because dust is no longer washed off the leaves (Uriu and Magnus, 1967; Beutel, 1981).

Reducing Irrigation

The creation of plant water stress by deficit irrigation or by use of saline irrigation water (osmotic stress) generally increases crop susceptibility to pathogens (Cook and Papendick, 1972; Schoenweiss, 1975; Duniway, 1977). Thus, although it is well known that wet soil conditions enhance Phytophthora root rot in safflower, water stress (e.g., by deficit irrigation) predisposes the crop to infection and thereby increases the severity of damage when irrigation is applied (Duniway, 1977). Deficit irrigation was noted by Oetting (1978) to cause water stress of turf, increasing its susceptibility to mite and insect damage. Horne (1980) found that deficit irrigation of corn or sorghum which causes moisture stress at the ear-formation or heading stages, promotes charcoal rot fungus at the base on the stalk. This can interfere with the transport of water and nutrients and result in weak stems with consequent lodging and yield loss. Deficit irrigation of a potato crop reduces the water content of tubers making them more susceptible to blackspot, even when only slight bruising occurs during handling (Kunkel, 1958). Deficit irrigation of fruit trees increases their susceptibility to sunburn and limb die-back and this in turn encourages canker of stone fruits, branch wilt of walnut and bark boring insects (Uriu and Magnus, 1967; Beutel, 1981).

By reducing the frequency and the quantity of irrigation applied to cotton the incidence of verticillium wilt can be reduced (Leyendecker, 1950; El-Zik et al., 1978). Reduction in the amount of water applied to cotton or the use of shorter-season varieties results in earlier harvests which enables earlier plow-under, thereby reducing the incidence of pink bollworm (El-Zik et al., 1978). Pinter and Butler (1979) documented the soil-inhabiting stages of pink-bollworms for cotton grown under different irrigation management options. They found that infrequent irrigation reduces the cooling of soil and thus tends to enhance the soil-inhabiting pupal stages of pink bollworm. Kittock (1980) found that by eliminating the final two irrigations of cotton the population of overwintering pink bollworms can be reduced 60%. The stress has the same effect as chemical termination of late bolls. If chemical termination is combined with elimination of one late irrigation, the overwintering pink bollworm generation is reduced 96%. Tests by Leigh et al. (1970) indicate that cotton growers can reduce the threat from insect pests through management of their irrigation and fertilization practices. They found that reducing the amount of post-planting irrigation water application significantly reduced lygus bug infestation on cotton.

Infrequent irrigation reduces the frequency of occurrence of high humidity in the plant "folio-sphere" and thereby reduces damage by anthracnose (Colleotrichum phomoides) to tomatoes (Raniere and Crossan, 1958), and by white mold (Sclerotinia sclerotiorum) to dry beans (Blad et al., 1978; Weiss et al., 1980). A reduction in irrigation frequency reduces the incidence of club root disease of Brassicae crops (Colhoun, 1953) and of Phytophthora root rot of cherry trees (McGill, 1980).

A reduction in irrigation frequency and/or regular weed eradication will reduce non-productive ET losses and also result in a lower population of weeds, many of which are known to harbor plant diseases and pests (Nalewaja, 1972). Transpiration losses from crops can be reduced by foliar sprays of antitranspirants (see CROP RESPONSES TO WATER DEFICIT category). Gale and Poljakoff-Mayber (1962) described how an antitranspirant film can have a prophylactic effect by providing a mechanical impediment to attacks by pathogens and pests on foliage. Thus, antitranspirant treatment reduced the incidence of powdery mildew on sugar beet leaves in both frequently and infrequently watered plots. Other tests by Gale showed that antitranspirant treatment of citrus foliage reduced infestation by scale insects.

Wastewater Reuse

Since most pathogens have specific optimal temperature ranges, the use of wastewater which has been warmed (e.g., thermally polluted water from power plants or agricultural tailwater that has been standing for a period of time) can cause a proliferation of soil pathogens such as Phytophthora (Duniway, private communication). The reuse of agricultural or municipal waste water for irrigation is known to spread various plant pathogens and pests, e.g., fungi, bacteria, viruses, nematodes, to crops (Cooke, 1956; Faulkner and Bolander, 1970a, b,; Thompson and Allen, 1975; Steadman, 1974 and 1979; Steadman et al., 1975 and 1979).

For example, Thompson and Allen, in a study of irrigation return flows to citrus orchards in Arizona, found that well water, initially relatively free from fungi, was heavily contaminated with phytophthora after passage through a citrus orchard. Steadman believes that some control in the spread of pathogens can be obtained by using tailwater from one cropped field on a different crop species which is not susceptible to the same pathogens.

Cropping Patterns

Changing cropping patterns to include crops with lower annual ET may result in water conservation at the farm and basin level. It may also provide the cropping diversity needed to prevent buildup of pathogens and pests in the same field. Ashworth and Huisman (1980) report that the inclusion of other crops in rotation with cotton reduces verticillium innocculum buildup in soil, and thereby enables continued planting of the high-yielding, but verticillium-susceptible, SJ-2 cotton in California.

PATHOGENS AND PESTS OF CROPS

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PRODUCTION COSTS

Because of numerous interactions between irrigation and other facets of crop production, agricultural water conservation can influence various costs of production. Inputs such as energy and labor have already been discussed elsewhere in this report. In this category we shall describe possible incidental effects of conservation on the quantity need, rather than the $ value, of inputs such as seed, fertilizers, herbicides and pesticides.

Profit Maximization

Water conservation actions (such as curtailing ET by deficit irrigation) which result in a lower farm water demand, may not provide crop yield maximization, but may give profit maximization because of a smaller need for expenditure on other inputs such as energy, labor, seed, fertilizer, etc. (Gogerty, 1972; Ayer et al., 1980; Anon., 1981). On-farm water conservation could also be achieved without reducing ET and therefore without entailing risk of crop yield loss. The potential for maximizing profits by reducing input costs for water, energy, etc., would then be even greater since gross income would not be reduced. Ayer and Hoyt (1981) reported that in Arizona when water costs were medium to high ($2.50-$5.00 per acre-inch) water applied to cotton, wheat and sorghum could be cut by 6 inches or more and result in maximum profits. It was pointed out by Ayer et al. (1980) that profit maximization is obtained when water is applied until the value of the marginal product (the $ value of the change in crop yield associated with each succeeding unit of applied water) equals the price of water. This conclusion is subject to modification if growers are averse to risk. The implications of profit maximization and risk are elaborated upon more fully in the section on "Economic Evaluation."

Reducing Production Costs for Fertilizer, Pesticides, etc.

In an investigation of the effect of irrigation on the activity of herbicides, Lange (1978) reports that by not applying too much water in an initial irrigation the pre-emergence herbicide Oxyfluorfen was not excessively diluted so more efficient use was made of the applied herbicide. In other words, by applying less water (0.5 in. instead of 2 in.) for herbicide incorporation, less herbicide need be applied to obtain a given level of weed control.

Longenbecker et al. (1969) found that the use of variable-row spacing for cotton reduced evaporation losses, the amount of water applied per irrigation, and costs for weed control, thereby reducing overall production costs. A reduction in plant population/ha could reduce ET/ha and also reduce the amount of seed, fertilizer and pesticide that need be applied (Musick and Dusek, 1969). Annual ET may also be reduced by changing cropping patterns. A comparative study of production costs for cropping alternatives is needed to determine whether there will be increases or decreases in various production inputs such as fertilizer, pesticides, seed, etc. (Such a study is being initiated under a separate agreement with DWR.)

As already pointed out (see MANAGEMENT category), drip and sprinkler irrigation systems have the capability of reducing applied water and also of applying fertilizer, herbicide, etc., at rates which are usually less than by conventional application methods. Thus, although initial capital costs are relatively high, a drip system can reduce operating costs because of more efficient placement and utilization of fertilizers and lower labor costs (Marsh et al., 1977).

If deficit irrigation is to be practiced in areas and times of water scarcity, it would become necessary to make more efficient use of available moisture, possibly by reducing plant population per hectare, e.g., by wide row spacing (Taylor, 1980). The seeding rate and perhaps other production inputs could then be reduced, with corresponding reductions in production costs. English and Nuss

(1980), in a paper entitled "Designing for deficit irrigation," point out that although yields may be reduced by deficit irrigation, production costs for seed, fertilizer, harvesting, and energy could also be reduced. Water conservation actions, such as reducing irrigation frequency, which curtail crop pests (see PATHOGENS AND PESTS category) could reduce the need for, and costs of, pesticides and their application (Leigh et al., 1970). An insufficient amount of soil moisture, which may occur if irrigation intervals are extended, can reduce herbicide activity and result in wastage of expensive herbicides (Lange, 1978). Infrequent irrigation may sometimes prove useful because it curtails weed population and thereby reduces the costs for labor and herbicides to control them (Delaney et al., 1978; Jacobs et al., 1978).

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SOIL--PHYSICAL EFFECTS

Since soil is the medium in which crops are grown and since irrigation is applied to the soil, it follows that irrigation management (quantity, quality and manner of application of water) will have some impact on the soil itself. The next section describes possible incidental effects of water conservation on soil salinity. This section describes effects on the physical properties of soil, such as structure, erosion, temperature and microbial activity.

Water Storage

The storage of water in deep surface reservoirs, such as Shasta and Oroville, produces relatively cold water which, while suitable for certain fish species, is less than optimal for irrigation of some crops because it lowers the temperature of the soil in the crop root zone (Wierenga and Hagan, 1966; Raney and Mihara, 1967). Many growers are able to store water in farm ponds by damming small gullies. This has the side benefit of reducing on-farm soil erosion (Henry and Gambell, 1980). Another form of water storage is to recharge groundwater aquifers by continuous surface ponding, but according to Wood and Bassett (1975) that can result in the growth of microorganisms in the ponded soil which, in turn, can reduce infiltration of water through the soil (Clark and Kemper, 1967).

Soil Management

By improving the soil's water infiltration rate (William and Doneen, 1960) and by proper irrigation management, surface ponding and the consequent E_W losses can be avoided. Avoiding ponding after irrigation will also prevent deterioration of soil structure and permit better aeration in the root zone (Howell and Hiler, 1974). It is well known that proper grading and levelling of land will improve irrigation application efficiency. However, excessive scraping can cause loss of good topsoil from parts of the field, resulting in lower yields and poor crop uniformity.

Unger (1975) and Box et al. (1980) point out that minimum tillage and stubble/straw planting (which can conserve water by reducing losses to E_s and RO) can reduce the erosion of soil by wind and water. Although various types of mulching can be useful for preventing evaporative losses of moisture from the soil surface, thereby ensuring adequate moisture for seedlings and shallow rooted plants, they can also affect the soil by reducing erosion and by either increasing or decreasing soil temperature (Gerard et al., 1959; Clarkson, 1960; Burrows and Larson, 1962; Kohnke and Werkhoven, 1963; Mannering and Meyer, 1963; Moody et al., 1963; Dhesi et al., 1964; Adams, 1966; Bennett et al., 1966; Joynson et al., 1966; Jordan and Sampson, 1967; Quashu and Evans, 1967; Kowsar et al., 1969; Liptay and Tiessen, 1970; Evanson and Rumbaugh, 1972; Unger, 1975; Box et al., 1980).

Irrigation Management

When flood-irrigating a field it is seldom realized that the weight of the water can cause soil compaction (6 ac. inches of water weigh nearly 680 tons). Strong (1961) therefore advocates applications of smaller depths of water, preferably by sprinkler irrigation rather than flooding. Avoiding excessive irrigation on heavy soils can not only reduce farm water demand, but also will increase soil microbial activity resulting in more efficient breakdown of organic matter and enhanced soil aggregation and nitrification (Clark and Kemper, 1967). The recently developed system of irrigating by surge-flow (Kotter, 1981) improves the application efficiency of water, provides a more uniform wetting of the soil profile over the whole field, and reduces soil erosion. Automatic regulation of on-off cycles of water flow to the field produces interesting effects. During the off-period consolidation of soil particles occurs as soon as the water subsides, so that in the successive on-flow cycles the soil becomes somewhat sealed near the head of the run (but is not as consolidated at the far end of the run), thus providing faster advance and more even infiltration of the water.

Reducing surface runoff by more efficient irrigation application will reduce soil erosion and loss of good top soil, particularly on fields with relatively large slopes (Fitzsimmons et al., 1977; Jackson, 1977; Jones, 1980). A reduction in the frequency of irrigation reduces the susceptibility of some soils to water erosion since most soil is eroded during the initial time of each irrigation (Mech and Smith, 1967), but increases their susceptibility to wind erosion because of the long time intervals when the soil surface is dry (Mech and Woodruff, 1967). These authors point out, however, that irrigating frequently with the intent of reducing wind erosion would be a waste of water since the surface of some soils would have to be kept constantly wet to prevent such erosion. Irrigation of alternate furrows, rather than every furrow, can conserve both water and soil by reducing erosion due to runoff (Mech and Smith, 1967).

Deficit irrigation results in extended periods when the soil remains relatively dry, a condition which reduces microbial activity and thereby affects organic matter breakdown, soil aggregation and nitrification (Clark and Kemper, 1967). Management of irrigation so as to conserve water could reduce groundwater pumping. This would then reduce dangers of land subsidence, surface cracking of fields, loss of soil structure and loss of groundwater storage capacity (Brown, 1977).

Wastewater Reuse

Tailwater systems enable reuse of excessive irrigation water applications. They can be incidentally beneficial by 1) preventing deterioration of soil structure, often observed when water stands at the lower ends of fields that do not have tailwater systems; and 2) increasing water temperature which, after the water is reused for irrigation, increases the temperature of the soil in the root zone and benefits crops such as rice (Schulbach and Meyer, 1979).

Irrigation with wastewaters which contain large amounts of sodium (e.g., water from alkali lands and some food-processing plants) causes deflocculation of the soil and thus reduces its porosity and infiltration capacity (Pearson, 1972; Cooperative Extension, 1977). Irrigation with sewage effluent can improve the physical properties of coarser soils because of the high organic content of the effluent (Schreiber, 1957).

The yield of water from watersheds may be improved when evapotranspiration losses are reduced by converting rangeland brush to forage species with lower ET rates. That, however, may result in soil erosion on rangeland during periods of heavy rainfall (Singer, et al., 1980).

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SOIL SALINITY

The previous section described how agricultural water conservation can affect physical aspects of soil. This section looks at the incidental effects on soil salinity. Since there are strong interrelationships between salts in irrigation water, salts inherent in soils and their parent rocks, and salts in both surface and groundwaters that receive agricultural return flows, the reader should also refer to the categories on WATER QUALITY and CROP RESPONSES TO WATER QUALITY.

Conveyance

Lining canals and ditches not only increases the efficiency with which water is conveyed from source to destination, but, by preventing seepage, it can also prevent salinization of adjacent land if the water has a relatively high salt content and the adjacent land is poorly drained (Walker, 1972).

Irrigation Management

Land levelling enables more efficient irrigation and even distribution of water. It also enables a more thorough and even leaching of salts by irrigation and rainfall, and prevents salt accumulation on high spots. Mulching the soil surface curtails E_s losses and thereby reduces the upward movement of salts thus reducing their accumulation in the upper root zone and also enabling more efficient leaching of salts out of the root zone (Fanning and Carter, 1963; Carter and Fanning, 1964). Miller et al. (1965) showed that intermittent, rather than continuous, ponding reduces the leaching requirement and enables more efficient leaching of salts from the root zone. Leaching by rainfall or normal irrigation, rather than by ponding, can reduce water requirements and provide more efficient removal of salts from the soil (Biggar and Nielsen, 1962). Off-season irrigation (in cool winter months) reduces evaporative losses and helps to fill the soil profile for later use by crops, thereby reducing irrigation in summer when evaporative losses are higher. The off-season irrigation also supplements rainfall in leaching salts out of the root zone (Cooperative Extension, 1975).

Water can be conserved by reducing deep percolation losses during irrigation, but if that reduction is greater than the required leaching fraction it can result in salt imbalance in the soil (Jackson, 1977; Miller et al., 1979). In the Imperial Valley, where irrigation water from the Colorado River has a high salt content, Robinson (1980) found that use of sprinklers instead of furrow irrigation saved 60% of the water used for germination and reduced the build-up of salts in the upper layers of seed beds. Drip irrigation can sometimes result in salt accumulation at the soil surface (Miller et al., 1979), but it should be remembered that the slow, but continuous, supply of water keeps the salts well diluted in the crop root zone. Subsurface irrigation (Anon., 1971) can not only reduce water requirements by 42% compared with a furrow system (Zetsche, 1964), but also reduces the concentration of salts in the root zone.

Wastewater Reuse

A tailwater system enables better salinity management by: 1) preventing a rise of shallow water tables since deep percolation can be more easily reduced; and 2) providing cheap supplemental water for leaching when needed (Schulbach and Meyer, 1979). The reuse for irrigation of wastewaters that have a high mineral content, however, can cause salt accumulations in soils and adversely affect salt balance (Bagley, 1967; Pearson, 1972). The use of saline power-plant effluent for irrigation could also result in soil salinization and therefore increases the need for additional leaching (Jury et al., 1978).

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TOXIC SUBSTANCES AND RESIDUES

Some irrigation management and water conservation practices can result in the transport and accumulation of toxic substances. Since some of the information pertinent to this subject is described elsewhere in this report (e.g., see categories on HAZARDS AND RISKS and on WATER QUALITY), these incidental effects will be described here only briefly.

As has already been pointed out, on-farm water conservation can be achieved by improving irrigation application efficiency in a manner that reduces surface runoff. Since runoff water often contains soluble pesticides as well as suspended sediment on which the less soluble pesticides adhere, there is some danger of toxic chemical build-up in receiving waters (Pionke and Chesters, 1973). Reducing RO losses and the use of relatively non-persistent pesticides should reduce this hazard. Wauchope (1979) reports that for most commercial pesticides total losses in runoff water are generally about 0.5% or less of the applied amount of pesticide. However, organochlorine insecticides may lose 1% and soil-surface wettable powder formulations of pesticides may lose up to 5%, depending on rainfall and slope of the field. Research is being conducted on soil and water conservation measures, such as minimum tillage, on runoff water quality.

Water conservation actions, such as reducing seepage and runoff losses, which reduce mosquito breeding sites (see MOSQUITO CONTROL category) or crop pest infestation (see PATHOGENS AND PESTS category) could reduce the need to spray hazardous chemicals which leave toxic residues (Anon., 1980).

Irrigation with agricultural and M&I wastewaters reduces the demand on fresh water supplies, but it may result in heavy-metal or other toxic-chemical buildup in soil, with possible uptake by plants (Baier and Fryer, 1973; Bouwer and Rice, 1977; Coop. Ext., 1977; Sadovski et al., 1978; WHO, 1980). Irrigation with wastewaters that are contaminated with colliform and other disease-causing organisms pose health hazards both on- and off-farm (Crook, 1980) and could result in lawsuits against farmers (Bouwer and Rice, 1977). In a seminar on the health aspects of treated sewage reuse, the World Health Organization (1980) pointed out that recharging groundwater with M&I wastewater poses a minimum risk from contaminants if water extraction from the aquifer occurs some time after, and at some distance from, the point of recharge. The WHO also concluded that the use of treated wastewater on crops to be eaten or handled raw can result in health problems from toxic substances in areas with a low level of technology since there is no assurance that treatment is always adequate.

The control of weeds is important, not only to reduce competition with crops, but because it prevents irrecoverable water losses by transpiration from non-productive vegetation. Nalewaja (1972) and Pringle (1978) point out that since some weeds produce toxic chemicals and irritants, their eradication can reduce this hazard to people and animals. Drost and Doll (1980) and Hager (1980) report that many weeds produce alleopathic chemical exudates which can inhibit the growth of neighboring plants. Thus, exudations from the roots of giant foxtail and quackgrass were found to inhibit the growth of neighboring corn plants, and a common annual weed, velvet leaf, adversely affected soybean growth. Control of these weeds could therefore prevent the deposition of toxic alleopathic chemicals in the crop environment and thus improve crop growth by an amount which is greater than that which can be attributed to competition alone.

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WATER QUALITY

Competitive demands for water by M&I users and agriculture have been increasing in recent years with the result that water is being reused more frequently than in the past. This has intensified concern over the quality of return flow waters and the impacts on receiving waters which are being increasingly reused. Since irrigated agriculture, in particular, has been indicted for excessive water wastage and for contaminating both surface and ground waters, this section describes the impacts of agricultural water conservation on water quality.

Storage and Distribution

Storage of water in multipurpose off-farm reservoirs not only enables timely release of water to meet irrigation requirements, but also provides the storage capacity needed for augmentation of low stream flows to maintain water quality (Law and Skogerboe, 1972; Zuckerman, 1979). The major unintended and irrecoverable loss of water from the reservoir itself is evaporation. E_W can be reduced by physical and chemical surface barriers provided wind and wave action do not break them up. However, some barriers, e.g., floating perlite, have been shown to degrade the quality of water by reducing the dissolved oxygen content and thereby adversely affecting fish and other aquatic life, particularly in hot weather (Cooley, 1972). Farm ponds provide a ready source of water for various farm needs and also are able to trap and hold a large proportion of pollutants that reach them (Henry and Gambell, 1980). The flooding of rice fields in northern California provides a form of off-stream storage during the summer. However, release of the rice flood water can result in inorganic nitrogen pollution of receiving waters, particularly if water is released about 6 weeks after planting (as is sometimes the case) so that recent pre-plant fertilizer applications, which may not have been incorporated into the soil, are partly washed out (Bilal et al., 1979; Tanji, 1979). Subsurface water storage through artificial groundwater recharge, according to Wood and Bassett (1975), has been found to change the quality of water for recharge because of the development of anaerobic bacteria during the ponding process. Bouwer (1974) pointed out that in arid regions the "low-rate" system of wastewater application to cropped land should not be used for groundwater recharge because after passing through the soil and picking up salts the percolated water has a higher salt content than the original wastewater effluent.

In some areas maintenance of adequate amounts of good quality water in groundwater aquifers depends on recharge by seepage from canals. Conserving water and improving the efficiency of its conveyance by lining canals which convey good quality water would, therefore, result in a degradation of groundwater quality. On the other hand, in areas where irrigation canals and laterals convey water which is relatively high in salt, e.g., Colorado River water conveyed in the Imperial and Coachella Valleys, would result in less salt loading from the seepage water (Evans, 1970; Skogerboe and Walker, 1972; Walker et al., 1978). In the Grand Valley of Colorado, Evans et al. (1978) estimated that canal linings reduce salt loading at unit costs ranging from \$190-\$700 per metric ton of salt removed. Seepage from canals and laterals contributed, respectively, 23% and 32% of the subsurface return flows and consequent salt loading in the Grand Valley area. Law and Skogerboe (1972) stated: "The economics of canal lining has been justified primarily on the basis of value of the water saved. The possibility that canal seepage may greatly increase the total contribution of dissolved solids to receiving waters has only recently been given serious attention."

Irrigation Management

Deep percolation of water can be reduced by improving irrigation application efficiency or by use of subsurface barriers. In saline areas that would result in less salt pickup from underlying geologic formations such as salty shales (Strathouse and Sposito, 1980) and thus reduce salinization of groundwaters (Law and Skogerboe, 1972). Gardner (1980) believes that in some soils which have subsurface impervious layers (plow pans), it can be advantageous to leave such layers intact because fertilizer leaching and groundwater degradation are ...

Reductions in water losses from farms through RO and DP by an improvement in irrigation application efficiency will generally reduce the total salt content of receiving surface and groundwaters (Sylvester and Seabloom, 1963; Woods and Orlob, 196: Law et al., 1970; Olson et al., 1973; King and Hanks, 1975; Fitzsimmons et al., 1977; Tanji et al., 1977; Huszar and Sabey, 1978; Ploss and Lyford, 1978; Interagency Task Force, 1979; Mielke and Schepers, 1979; Pratt et al., 1979; Tanji et al., 1979; Cooperative Extension, 1980). However, in the Interagency Task Force Report (1979) it is pointed out that very high irrigation application efficiencies may result in higher concentrations of pollutants because of lower volumes of return flows from fields and thus cause localized water quality problems.

Bingham et al. (1971) studied a 960-acre citrus watershed and found that of the water entering the watershed 40-50% went out as effluent drainage. The nitrate concentrations of the effluent were as high as 87 ppm, averaging 50-60 ppm. This NO_3 loss (about 45% of the applied fertilizer nitrogen) could contribute to degradation in the quality of receiving waters. The authors note, however, that in the Imperial Valley, where much higher N applications are used, effluent waters are relatively free of NO_3 because of its reduction to gaseous N_2 in the vicinity of the water table or tile drain.

As part of an important study on "Nitrate in effluents from irrigated lands", funded by the National Science Foundation (Pratt et al., 1979), Tanji et al. (1979) computed that water fluxes and annual mass emissions of nitrogen below the 3m-deep root zone depended on whether irrigation was applied at 1/3, 3/3, or 5/3 of the ET rate. Thus, with deficit irrigation (1/3 ET) no N moved below the root zone, but at 100% irrigation efficiency (3/3 ET) about 1 kg N/ha/yr moved below the root zone, and at 60% efficiency (5/3 ET) 27 kg/N/ha/yr (of the 180 kg N/ha applied as fertilizer) was leached below the root zone and thus could contribute to groundwater pollution. The overall objective of the NSF Project (Pratt et al., 1979) was to develop capability to predict NO_3 concentration and quantity of NO_3 nitrogen in drainage waters from irrigated lands. The Report concludes that management strategies for increased N use efficiency and reduced NO_3 leaching include: 1) irrigate for greater efficiency to reduce drainage; 2) avoid N application in excess of that needed for maximum crop yield; 3) manage fertilizer to control source, timing and placement. The Report also found that while mass emission of NO_3 was correlated with N input and with drainage volume, it was most highly correlated with the product of the two.

Reductions in surface RO from fields, especially with relatively steep slopes, will improve the quality of tailwater by reducing sediment loading (Fitzsimmons et al., 1977; Miller et al., 1977; Ogg et al., 1980). Gossett and Whittlesey (1976), in a study on five different crops, found that a furrow cut-back irrigation system consistently showed higher irrigation efficiencies and lower sediment yields and N leaching losses than a simple furrow system. For example, in potatoes sediment losses were 8T/ha with the cut-back system, but 20T/ha without it.

If irrigation is managed so that DP is reduced to just enough for leaching (minimum leaching concept), it should reduce the degradation of groundwater quality (van Schilfgaarde, 1974; Jury et al., 1978). Any water conservation action that reduces groundwater pumping in coastal areas will reduce the highly damaging effects of groundwater salinization caused by intrusion of seawater (Scott, 1979).

When irrigation systems, such as sprinkler and drip, are properly managed there can be reductions in both on-farm water demands and salt loading from irrigation return flows (Patterson and Wierenga, 1974; Kepler and Pitts, 1978; Walker et al., 1978). This is particularly true early in the irrigation season when there are larger accumulations of salts in the soil profile. Rauschkolb et al. (1979) emphasized that irrigation management techniques which lead to greater amounts of deep percolation may result in lower NO_3 contrations in the soil profile, but contribute to transfer of a greater total amount of N to receiving waters. If water is managed in a manner which improves the efficiency of utilization by crops, the NO_3 concentration in the root zone may be high, but mass emission below the root zone would be low.

The use of irrigation scheduling services (Ploss and Lyford, 1978) often reduces excessive losses to RO and DP and thus results in less sedimentation and a smaller mass emission of salts in return flows and subsequent improvement in regional environmental quality (Skogerboe et al., 1979; English et al., 1980). Kepler and Pitts (1978) state: "Irrigation scheduling by itself is not a panacea for controlling pollution from return flows. Combined with improved on-farm practices it may be quite effective, however." These authors also estimated percentage reductions (compared to furrow irrigation) in pollutant loading for various management options including irrigation scheduling, canal lining, other irrigation systems, tailwater pumpback, etc. (see p. 155 of their Pollution Control Manual for Irrigated Agriculture).

Cropping Practice

The choice of crops and cropping sequences can affect the amount of water annually consumed in ET on a farm, and also can affect the application and use of fertilizer nutrients by crops. Thus, Adriano et al. (1972) point out that single- instead of double-cropping reduces fertilizer use and the chance of nutrient leaching which causes pollution of receiving waters. Pratt et al. (1979) conclude that NO_3 leaching can be reduced by selecting crops such as sugar beets that efficiently use available N or crops such as alfalfa that use soil N efficiently and fix N from the air so that less fertilizer N need be applied. Howe and Orr (1974), investigating the effects of agricultural acreage reduction on water availability and salinity in the upper Colorado River basin, concluded that not only would agricultural water demands be reduced, but that there would be a considerably smaller amount of salt loading from irrigation return flows.

Wastewater Reuse

Although farm irrigation application efficiencies are low in many areas, basin efficiencies in some areas, e.g., Tulare basin, are high because of the reuse of agricultural return flows. Doneen and Henderson (1957), however, pointed out that continued reuse of agricultural water contributes to the degradation of the quality of those waters. On the other hand, the reuse of agricultural tailwater (Bondurant, 1970) results in less pollution of receiving waters because dissolved and suspended fertilizers and pesticides are returned to the cropped fields (see FERTILIZER AND NUTRIENTS category).

The use of brackish water for irrigation (e.g., Jury et al., 1978) reduces the demand on fresh water supplies, but extra quantities of good-quality water are needed for periodic leaching of salts from the root zone, and consequently there could be significant mass emissions of salts to the groundwater (Willey, 1980). The blending of brackish (or other wastewater) with irrigation water of good quality results, of course, in a quality degradation of the latter.

Several researchers (Bouwer, 1968; Lau, 1974; Feigin et al., 1978; Lance, 1978) have pointed out that reuse of partially or improperly treated wastewater for irrigation can result in health hazards (see HAZARDS AND RISKS category) from nitrates and toxic chemicals that may reach receiving waters, such as groundwater aquifers which supply water for domestic use. Bouwer (1974) explained that contamination of groundwater can be minimized by applying only small amounts of wastewater per unit of cropped area. While this may be environmentally beneficial, the "low-rate" system is disadvantageous from the point of view of wastewater disposal (see DRAINAGE DISPOSAL category) since large disposal areas would be needed (at 1 inch/week, about 260 acres are required per 1 million gallons per day of wastewater). On a more optimistic note, however, the application of reclaimed wastewaters on land for crop irrigation can be looked at as a means of environmental enhancement since the soil and vegetation remove some of the contaminants before they can reach receiving waters (Ayers, 1971; Coe and Laverty, 1972; Smith et al., 1972; Boyle Engg. Corp., 1981).

Institutional Mechanisms

Vlachos et al. (1977), in describing a process for identifying, evaluating and implementing solutions for irrigation return flow problems, state that institutional and economic changes which encourage efficient use of existing irrigation supplies and systems will result in a reduced mass emission of pollutants in return flows. Horner and English (1976) and English et al. (1980) suggest that adjusting the cost of irrigation water to account for costs associated with the quality of return-flows and their disposal would result in a decrease in return flows and therefore less degradation in the quality of receiving waters. Huszar and Sabey (1978) believe that current policies for correcting the problem of irrigation return flow pollution "tend to attack the symptoms of the problem, rather than its cause." They conceptualize that instead of our present system for allocating irrigation water (the cause of the problem), creation of a water rental market would induce profit-maximizing farmers to use the water supply more efficiently and rent the surplus to other irrigators, thereby reducing return flows and their associated pollution.

Knight and Simmons (1980) prepared a bibliographic guide to information sources on the subject of water pollution, including sections on "Agricultural pollution" (pp. 139-143) and on "Social, economic, and political aspects of water pollution" (pp. 163-172).

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WEEDS

The control of weeds in cropped fields is normally an on-going operation on any well-run farm since weeds compete with crops, not only for water, but also for nutrients and light. Benedixen et al. (1979 and 1981) prepared annotated bibliographies of weeds as reservoirs for organisms affecting crops. (See also PATHOGENS AND PESTS category.) In this section we have described the effects of various water conservation actions on weed populations and their control.

Lush growth of weeds in and along unlined ditches is a common sight. Lining canals and laterals or use of pipes to convey water will reduce seepage losses and the opportunity for weeds to proliferate and transpire into the air water which is intended for use further down the line (Scott, 1957; Dept. of Water Resources, 1976). Canal lining also reduces aquatic weeds which clog canals and phreatophytic weeds which tap groundwater tables that are fed by canal seepage. The diversion of excess winter and spring flows to recharge groundwater is a conservation measure that has been mentioned several times in this report. Hall (1957) believes that winter flooding of alfalfa fields would enable such recharge and would simultaneously provide good weed control in alfalfa fields without damaging the crop, provided flooding periods are not over-extended.

Solid-barrier mulches, such as polythene sheeting, simultaneously reduce unproductive soil-surface evaporation and weed transpiration by successfully controlling weed populations (Bennett et al., 1966). Any weed control process, whether physical or chemical, results in a reduction in irrecoverable transpiration losses. The incidental effects of weed control include various benefits which have already been described under the categories of AIR QUALITY, CROP RESPONSES TO WATER DEFICIT, PATHOGENS AND PESTS and TOXIC SUBSTANCES. Recently, however, Altieri (1981) provided evidence that weeds may augment biological control of insects, and that outbreaks of some insect pests are more likely to occur in weed-free than in weed-diversified crops.

Longenbecker et al. (1969) found that variable row spacing of cotton reduced irrigation and soil surface evaporation and was also beneficial in providing better control of weeds. Delaney et al. (1978) and Jacobs et al. (1978) provide evidence that a reduction in irrigation frequency can not only reduce farm water demand but also reduce the population of some weeds because of longer time intervals of relatively dry soil. Drip irrigation or other systems, such as spitters, that provide only localized wetting of soil, help to control weed growth because of the intervening dry areas (Marsh, 1977).

Tailwater systems enable water conservation, but also reduce the growth of weeds at the lower ends of surface-irrigated fields because excessive moisture at the tail end of the field is avoided (Fishbach, 1972; Schulbach and Meyer, 1979). Tailwater sumps, on the other hand, can result in the proliferation and spread of aquatic and phreatophytic weeds. Jackson (1977), in describing possible environmental damage associated with irrigation, points out that reuse of irrigation water, e.g., through a tailwater return flow system, contributes to the spread of various species of weed seeds.

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WILDLIFE

All life, whether animal, bird, reptile, insect, fish, or plant, is dependent on water for survival. It is, therefore, not surprising that diversion and manipulation of water by humans will affect wildlife. In this section we describe some effects of agricultural water conservation actions on wildlife. Since some of the impacts on fish and other aquatic life in major streams and rivers were described in the INSTREAM NEEDS category, they will not be covered here.

About 10 percent of the water diverted for agriculture seeps out of district canals and laterals and farm head ditches. While the lining of canals improves conveyance efficiency by reducing seepage losses, it also can reduce wildlife habitats, such as marshes, that are dependent on canal seepage (Dept. of Water Resources, 1976; Interagency Task Force Report, 1979).

Farm ponds not only conserve water for later use, but also provide refuge for various forms of wildlife (Ogle, 1971; Schuhart, 1978; Henry and Gambell, 1980). Several systems have been suggested for conserving water by reducing evaporation from reservoirs and ponds. Cooley and Brent (1972) report successful curtailment (by 19 percent) of E_W by spreading perlite ore on pond surfaces. They also found that in cool months the perlite did not adversely affect fish growth, but a complete perlite cover in warm months was detrimental to fish, partly because of a reduction in oxygen content. The reduction of pond evaporation by monolayers formed by surface spreading of long chain alcohols such as hexadecanol (cetyl alcohol) was reported by Wiltzius (1967) to also adversely affect insect emergence, including an 80-100 percent reduction in mosquito emergence (see MOSQUITO CONTROL category), provided a complete monolayer could be maintained. However, he observed no toxicity to fish, animals, reptiles, and waterfowl. Timblin (1957) and Frenkiel (1965) reported no toxicity to aquatic life when hexadecanol was used as an evaporation suppressant.

As pointed out earlier in this report (see AIR QUALITY category) the use of stubble/straw mulching reduces E_s and replaces agricultural burning of barley and wheat straw in early summer. This conservation action can also reduce the adverse effects of agricultural burning on wildlife such as nesting wildfowl (Fritzell, 1975).

When farm water demands are curtailed through various water conservation actions it can result in less drawdown of surface reservoirs. McAfee (1980) points out that this can have varying effects on aquatic life, depending on the characteristics of the reservoir and on the rate and timing of drawdown. On the farm itself, a reduction in tailwater runoff would result in less exposure of water to the sun and consequently lower water temperatures. Since runoff water from agricultural areas sometimes flows to wildlife areas, the amount of water and its temperature can affect the habitat and aquatic life.

Phreatophytic non-crop vegetation has long been known to be a water waster since it acts as a biological pump to transfer subsurface water to the atmosphere where it is irrecoverably lost. Eradication, by chemical and mechanical means, seemed to be a feasible water conservation action (Culler, 1970), but it also results in a loss of wildlife habitat and can have other severe ecological implications (Campbell, 1970; Davenport, 1977). As an alternative to eradication, riparian phreatophytes can be sprayed with a non-toxic antitranspirant (AT) which has been shown in field studies to reduce salt-cedar transpiration by 25 percent without destroying wildlife habitat. However, AT spraying by helicopter could adversely affect bird nests and egg hatchability (Davenport et al., 1978 and 1979).

As pointed out at the beginning of this section, water diversions and transfers by man cannot but have some effect on wildlife. Thus, water transfers through an agricultural water purchase plan may enable more efficient utilization of water, but it could also have beneficial or adverse impacts on wildlife and fisheries in the environs of the water seller and of the water purchaser (Dept. of Water Resources, 1979).

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GENERAL

As the name denotes, this category includes broad concepts or groups of water conservation actions and their general incidental effects. Some of these ideas have already been expressed in the introductory sections of this report but bear repeating because of their broad implications.

Some "losses" of water (such as leakage, spillage and seepage during conveyance, and deep percolation and surface runoff during irrigation application) are recoverable (Davenport and Hagan, 1979a and b). Reduction of such "losses" and/or retrieval and reuse of the "lost" water provides local but not necessarily basin- or state-wide water conservation. The incidental effects of conservation actions including recoverable water are numerous and have been described elsewhere by Davenport and Hagan (1980) and in this report under most of the specific categories, e.g., CROP RESPONSE TO WATER QUALITY, DRAINAGE DISPOSAL, ENERGY, GROUNDWATER DEPTH, INSTREAM NEEDS, MOSQUITO CONTROL, PATHOGENS AND PESTS, WATER QUALITY, WEEDS, WILDLIFE.

Other losses of water are irrecoverable because they 1) are transferred to the atmosphere as vapor through evaporation from water and soil surfaces, and, chiefly, transpiration from plants; and/or 2) flow to highly saline sinks from which recovery is not feasible (Davenport and Hagan, 1979). A reduction in these water losses could reduce both local and basin- or state-wide net water demands. However, the net impacts of ET reduction (Davenport and Hagan, 1980, 1981) would necessitate evaluations of trade-offs between the value of crop yield loss (assuming substantial reductions of T occur) and the value of savings in production inputs such as water, energy, labor, fertilizer, etc. The net impacts of reductions in flows to saline sinks (particularly river outflows to the Pacific Ocean and drainage to the Salton Sea in the Imperial Valley) would necessitate evaluation of trade-offs between the value of stream flow diversion for various uses and the values of the undiverted water to Delta and coastal needs, salinity repulsion, fish and wildlife, navigation, recreation, and other in-stream values. These impacts, beneficial and costly, have been identified, though not evaluated, under various categories of incidental effects in this report.

Sonnen et al. (1980) evaluated incentives for agricultural water conservation by interviewing 13 farmers in 4 different irrigation districts. One of their conclusions was that because the conservation actions are made on-farm, the growers are most interested in benefits accruing to themselves. Their next order of interest would be the effects on their neighbors, then the district, and lowest in priority would be impacts of their conservation actions at the basin or state level.

Pressures from the public and from federal and state governmental agencies (including an Executive Order from the Governor of California) create incentives (whether voluntary or involuntary) for agricultural water conservation actions. However, there is a need to assess the real values of various water conservation actions and, with respect to benefits, to produce answers to questions on: what? where? how much? duration?; also, to whom do the various benefits and costs accrue? (Turner and Bousseloub, 1979; Davenport and Hagan, 1979b; Sonnen et al., 1980).

Another type of pressure suggested for conservation of agricultural water is to price it at levels approaching the marginal costs (General Accounting Office, 1981). This would then reduce the demand, or "need" (Young, 1980) for new water projects and reduce the associated adverse impacts on the environment (Willey, 1980).

Since considerable interest has been shown (mainly by those not active in the business of farming) in the idea of changing cropping patterns to reduce farm water demands, presumably by reducing seasonal ET, there is a need to study the complexities and varied impacts on soil, markets and related industries and to relate these impacts to the value of savings in water, energy and other production inputs resulting from a crop change. These aspects are to be studied under a separate contract with the California State Department of Water Resources.

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SUMMARY OF INCIDENTAL EFFECT TABULATIONS AND DESCRIPTIONS

In the preceding tabulations and text we have identified well over 400 incidental effects, either beneficial or costly, of various agricultural water conservation actions. In *Table 5* we have counted the number of effects in the 23 categories of incidental effects, noting whether they 1) are beneficial or costly, and 2) have impacts on-farm, off-farm or both on- and off-farm. It should be clearly understood that *the number of beneficial or costly effects counted is not an indication of the importance or severity of the impact.* That judgment can only be made through economic analyses, assuming that effects can be appropriately quantified. Even then, some subjective judgments would have to be made and consideration given to factors of crop and site specificity.

With these stipulations in mind, Table 5 tells us that the largest count of effects was in the category of "Crop Responses to Water Deficit or Excess" (68), followed by "Management and Planning," (34), "Energy" (31), "Water Quality" (27), and "Pathogens and Pests of Crops" (26). Although the number of benefits for the category of "Crop Responses to Water Deficit or Excess" was double that of the costs, one cannot safely conclude that water conservation actions will result in more benefits than costs in terms of crop yield. Site- and crop-specific analyses would have to be made for each specific conservation action (e.g., recycling tailwater or deficit irrigation) to quantify the effect on crop yield. Just the analysis of the effects on crop yield of deficit irrigation is a complex task because it involves production functions (of ET vs. crop yield) which must include the timing, severity and duration of water stress. The total number of benefits (283) was about double the number of costs (138), but again this is more an indication that many incidental benefits are possible when agricultural water is conserved than a statement that there will always be

Table 5. Summary of the number of incidental effects (beneficial or costly) of agricultural water conservation actions for various categories and of the incidence of their impact. *(NOTE: The number of effects counted does not indicate the importance or severity of effects.)*

Incidental Effect Category	Effect			Incidence		
	Benefit	Cost	Total	On-Farm	Off-Farm	Both
Air Quality	3	2	5	-	1	4
Crop Responses to Water Deficit or Excess	46	22	68	64	-	-
Crop Responses to Water Quality	9	8	17	16	-	-
Drainage or Wastewater Disposal	8	-	8	2	1	5
Energy	21	10	31	13	14	3
Fertilizer and Soil Nutrients	14	3	17	17	-	-
Food and Fiber Production	3	3	6	-	4	2
Groundwater Depth	8	2	10	2	-	8
Hazards and Risks	6	7	13	8	2	3
Institutional	10	13	23	6	8	7
Instream Needs	11	3	14	1	12	-
Labor	10	2	12	10	1	1
Land Utilization	12	4	16	9	2	4
Management and Planning	22	12	34	22	8	3
Mosquito Control	12	1	13	1	1	11
Pathogens and Pests of Crops	16	10	26	23	-	3
Production Costs	10	2	12	11	-	-
Soil-Physical Effects	13	10	23	21	-	1
Soil Salinity	9	4	13	13	-	-
Toxic Substances and Residues	5	2	7	1	1	5
Water Quality	18	9	27	2	10	15
Weeds	8	2	10	7	3	-
Wildlife	9	7	16	-	7	7
TOTALS	283	138	421	249	75	82
GRAND TOTALS	421*			406*		

* The difference in these totals occurs because 15 items were counted as being either beneficial or costly.

a *net benefit*, i.e., that the value of the benefits exceeds that of the disbenefits. It should also be kept in mind that our tabulations and descriptions in the preceding pages have not included the $ costs that may be incurred by a water conservation action (e.g., the cost of land levelling or of a drip system when attempting to improve irrigation application efficiency).

Table 5 also provides a summary of the number of impacts of agricultural water conservation that occur on-farm, off-farm, or both. Since most of the conservation actions are taken on-farm, it is not surprising that the count of impacts is about three times greater on- than off-farm. Nevertheless, it is very significant that 75 impacts were noted to be off-farm, plus 82 effects that would have impacts both on- and off-farm. Thus, we counted 157 effects of agricultural water conservation that could have some impact on areas (and their human and wildlife inhabitants) other than the farm where the conservation action was taken. With respect to individual categories of incidental effects, needless to say, all or nearly all of the effects were on-farm for the categories of "Crop Responses," "Fertilizers and Soil Nutrients," "Labor," "Pathogens and Pests of Crops," "Production Costs," and "Soil." The effects were mainly (or exclusively) off-farm for "Air Quality," "Drainage or Waste Water Disposal," "Food and Fiber Production," "Groundwater Depth," "Instream Needs," "Mosquito Control," "Toxic Substances and Residues," "Water Quality," and "Wildlife."

"Energy," one of the more important categories in this age of increasingly expensive fuels and other power sources, included water conservation effects that had a number of significant impacts on-farm as well as off-farm, depending on the specific conservation action. The most relevant effect for farmers would of course be conservation actions that reduce farm water demand on farms which obtain all, or most, of the irrigation supply from deep wells.

In general, the most pertinent *on-farm* effects are those which have impacts on the *business* of farming and thus affect net returns. These therefore include:

1) production input factors such as energy, fertilizer, labor, management, and other production costs; and 2) production output (mainly crop responses to water, pathogens and pests, etc.) and hazards and risks which affect the yield of marketable produce. Farmers also should have, and most do, a concern for water conservation actions that might have long-term effects on their farms' productivity. These include on-farm effects in the categories of drainage disposal, groundwater depth, land utilization, and the quality of their soil and water.

In general, the most important *off-farm* effects of water conservation fall under the umbrella of that convenient term, "the environment." These include the categories dealing with the quality of air and water and include the hazards of toxic substances and impacts on instream needs and wildlife.

If the ultimate goal for identifying the incidental effects of agricultural water conservation actions is to provide added incentive to farmers and purveyors to conserve water, then it is important to recognize whether that water saving is solely on-farm(usually due to reduced losses of recoverable water) or if there is also a saving for the hydrologic basin and the State(due to reductions in irrecoverable water losses). Planners for State water agencies who are concerned with reducing projected net water deficits must therefore recognize whether water losses are recoverable or irrecoverable.

Incidental effects resulting from reductions in *recoverable* losses (leakage, seepage, spillage, deep percolation, run off) fall into a variety of categories some of which would concern the farmer and others which would be off-farm concerns. In terms of water quantity savings, the farmer would generally benefit from reducing recoverable losses.

Incidental effects resulting from reductions in *irrecoverable* losses (evaporation and transpiration and flows to highly saline bodies) usually involve 1) curtailment in crop yield (if T is reduced) but can include savings in some production costs; and 2) impacts on in-stream needs. In terms of water quantity savings, both the farmer and the state would benefit. Net benefits must consider costs vs. savings for both the quantity of water saved and the incidental effect.

Finally, the reader is again reminded that the counts in Table 5 provide only some interesting statistics on the number and variety of incidental effects of agricultural water conservation, some beneficial and some costly, which can have impacts not only on-farm but also off-farm. These numbers, as also the descriptions of effects in the preceding sections of this report, do not provide the information needed to quantitatively determine (to the extent that current information permits) the net benefits and costs, and their incidence, of various agricultural water conservation actions. The following section of this report describes the economic methodology and input data that are required to evaluate incidental on-farm effects of agricultural water conservation.

ECONOMIC EVALUATION OF INCIDENTAL EFFECTS OF AGRICULTURAL WATER CONSERVATION

INTRODUCTION

The general insights that economic theory provides for agricultural water conservation are relatively straightforward. The idea that water conservation is desirable suggests that water use is currently excessive or wasteful in some sense. In general economic terms, excessive use of a resource usually implies that it is underpriced. Well functioning markets normally adjust to ensure that just the right amount of a scarce resource is used or allocated among the competing demands for it. In economic terms, then, the "need" for conservation or the saving of some resource is symptomatic of a situation in which the resource is not correctly priced.

There is a large body of literature that attests to the fact that water in California is normally priced below its true scarcity value (see, for example: Hirshleifer, DeHaven, and Milliman, 1969; Howitt, 1977; and Rand Corporation, 1978).[1] The possible explanations for underpricing of a resource are two. First, it may be true that the resource in question is not traded in well functioning markets. The flaws in the market structure or institution serve to depress its price with the result that too much is used or consumed. A second explanation for underpricing is applicable only in certain situations. This explanation holds that there are certain costs which a producer (or consumer) can shift to his neighbors or to society at large. These costs, which are sometimes called external costs, are generally not accounted for by the individual who makes the decision to incur them since he is able to shift them to some other party. The discharging of contaminants into a waterway is an obvious example of external costs. Producers shed the costs of disposing of some of their wastes onto other users of the river. The cost of waste disposal to the producer is thus zero or

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[1] See list of References at end of report.

nearly so and the producer has an incentive to overutilize the scarce waste assimilating capacity of the stream.

In this section, the distinction between these costs is delineated more carefully and the pertinence of the distinction for agricultural water conservation is examined. Subsequently, various economic methods for evaluating the types of costs relevant to agricultural water conservation are discussed and some illustrative examples are presented. Finally, some general conclusions about the desirability of agricultural water conservation and the potential means of achieving it are drawn.

SOME CLASSES OF COST

At the outset it is important to distinguish between private costs and external costs. Private costs are those borne by an individual, acting as a consumer or producer, who makes a decision to purchase or produce some good or service. The costs that that individual bears as a consequence of the decision are said to be private costs. If prices (the cost paid for something or the cost incurred in producing it) actually reflect all costs, then a producer or consumer bears the full consequences of his production or consumption decisions. Often, however, prices do not fully reflect all of the costs of production or consumption and those costs not included in the price are said to be "external" to the decision. The individual has no incentive to consider these costs in making economic decisions, yet society must consider them since one or more of its members bear them involuntarily.

The basic importance of this distinction for agricultural water conservation lies with the fact that the appropriate way of viewing and treating the costs and benefits attendant to water saving actions depends crucially upon whether the costs (or benefits) are private or external. If all of the costs and benefits of agricultural water conservation are private, then individual water users can be relied upon to account for them in their water use decisions so long as water is priced according to its true scarcity value. If individuals account fully for the impact of their actions, then it follows that there is no need for some external agent to be concerned about regulating economic behavior.

A different conclusion may be drawn with respect to certain classes of external costs, however. When the cost or benefit of an activity to the individual producer or consumer is less than the cost or benefit to the society, an externality or third party effect is said to exist. If the effect is an external cost, then too much of the good is being produced from a social standpoint because producers (or consumers) have no incentive to account fully for all the impacts of their decisions. In these instances, society may be made better off by restricting some of the production (subject to some very important assumptions). If the effect is an external benefit, then too little is being produced and an expansion in production would increase the total economic benefit to society as a whole.

In more formal terms, an externality alters the technical relationships between inputs and outputs. In other words, the externality has caused a shift in the production functions of other producers or in the utility functions of other consumers. Such external costs or benefits are termed "technological externalities." They create a misallocation of resources and, as a consequence, lower economic welfare below its optimum achievable level.

Another type of external effect is called a "pecuniary externality." This type of externality affects the financial positions of those (other producers or consumers) not party to the decision, but does affect the options for production or consumption available to others. Such pecuniary externalities are created when the action of one person or firm causes a change in the prices faced by others. Such a change in prices may cause some redistribution of income or wealth but need not result in a misallocation of resources. For example, a grower who installs an automated irrigation system may cause some farm workers to lose their jobs and these workers suffer a pecuniary externality. Income has been transferred away from them and to the manufacturers of irrigation systems.

Pecuniary externalities are simply the adjustments in prices that flow from everyday workings of economic markets in response to changing conditions of supply and demand. Pecuniary externalities are not true externalities in the sense that technological externalities are because pecuniary effects do not result in the misallocation of resources and do not affect the economic welfare of the society as a whole.

The resource allocations due to technological externalities are often justification for some type of governmental corrective action. Such action is usually intended to induce the creator of the externality to account for it. Pecuniary effects require no government action to correct allocation, though in many instances they may produce a distribution of income that seemed to be undesirable.

In analyzing the economic impacts of changing levels of water use, it is important to distinguish between these different classes of cost both because the general methods available for estimating them may differ and because the implications of each type of cost for the public sector may differ. As a general rule, the costs (or benefits) associated with on-farm incidental effects are private costs while those associated with off-farm effects are external costs. Where the costs (or benefits) of off-farm effects result in a misallocation of resources they are technological in nature. Where they merely affect the structure of prices, they are pecuniary.

In *Table 6* the various classes of incidental effects identified in this report have been listed and categorized according to whether their effects are strictly private, strictly external, or some combination of both. In the majority of incidental effect categories, the impacts are both private and external. To the extent that they are private, growers can be relied upon to account for them. To the extent that they are external, they will tend to be ignored. Consideration is given next to the basic theory of production which forms the conceptual basis upon which private costs are customarily evaluated.

Table 6. Classification of Economic Costs. X = a clear cost; (X) = only minor or inconsistent cost.

Incidental Effect	Type of Impact: Private	External
Air Quality		X
Crop Response to Water Deficit or Excess	X	
Crop Response to Water Quality	(X)	X
Drainage on Waste Water Disposal		X
Energy	X	
Fertilizers and Soil Nutrients	X	
Food and Fiber Production	X	
Groundwater Depth	X	X
Hazards and Risks	X	X
Institutional	X	X
Instream Needs	(X)	X
Labor	X	
Land Utilization	X	X
Management and Planning	X	X
Mosquito Control	(X)	X
Pathogens and Pests of Crops	X	X
Production Costs	X	
Soil Physical Effects	X	(X)
Soil Salinity	X	
Toxic Substances and Residues	X	X
Water Quality	X	X
Weeds	X	(X)
Wildlife		X

ECONOMIC THEORY OF PRODUCTION

Efficiency of Resource Use

A review of the literature suggests that there is some inconsistency and confusion about the most desirable or efficient place to operate along any given production function. Much of the work by agronomists is directed toward the goal of establishing the level of water input necessary to achieve maximum yield per acre. This particular goal is implicit in all efforts that are intended to ensure that "water does not become limiting." Another measure of desirability frequently encountered in the production function and irrigation literature is that of maximum "water use efficiency". Maximum water use efficiency is said to exist when the crop yield per unit of water input (usually dry matter per unit of evapotranspiration), is maximized. A careful analysis suggests, however, that these two goals are inconsistent.

The curve in *Figure 4 (a)* represents a conventional though hypothetical production function. It is also called a total physical product curve. It depicts the locus of crop yields (on the vertical axis) a function of water input (on the horizontal axis), holding all other factors constant. The production function or total physical product curve can be defined as:

1) $Y = f(W)$

where

Y = crop yield

W = water input

f = a rule relating input to output

Two related concepts can be introduced. Average physical product, which is simply output divided by input, can be written as:

FIGURE 4

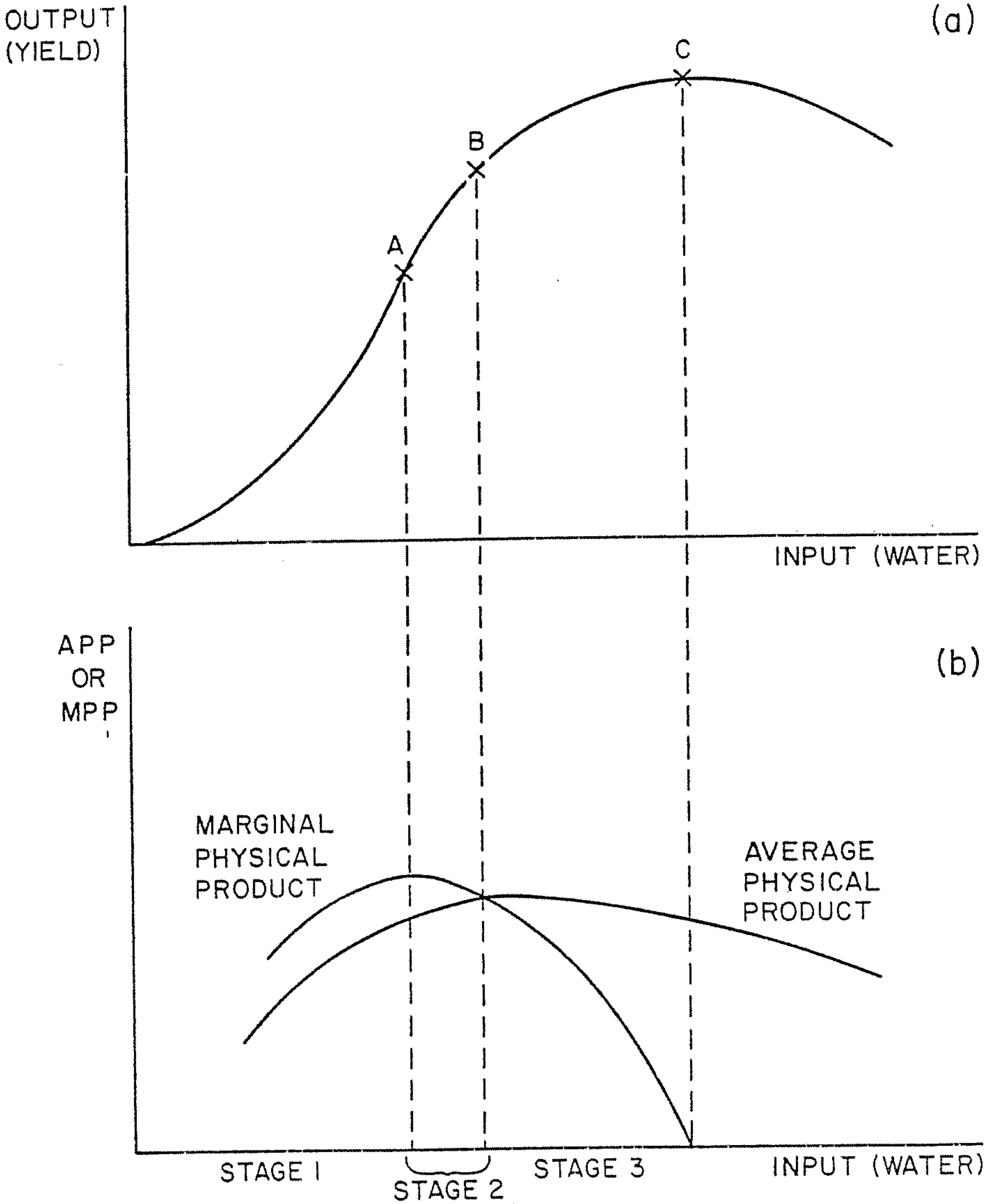

Figure 4. Response of output (yield) to input (water), and relationship between total, average, and marginal physical product.

2) $APP = Y/W$

Maximization of water use efficiency as conventionally defined, involves maximizing the average physical product. The marginal physical product is defined as the change in yield or output associated with the addition of one or more unit of input, or in this case, water. It can be written as:

3) $MPP = \partial Y/\partial W$

The marginal physical product and average physical product curves associated with the production function in Figure 4 (a) have been plotted in Figure 4 (b).

The inconsistency between maximum yield and water use efficiency can be demonstrated first by noting that maximum yield occurs at point C on the total physical product curve while maximum water use efficiency, the point where average physical productivity is maximized, is at point B. The simple mathematics of optimization can be used to show that this conclusion holds generally. Total physical product or output is maximized where the marginal physical product is equal to zero. Additionally, it can be demonstrated that average physical product is always maximized where it is equal to marginal physical product. As a consequence, maximum water use efficiency (maximum APP) and maximum yield could only be equivalent if APP is maximized at zero. Yet, average physical product cannot be zero except where there is no production at all and thus the inconsistency between the two concepts is established.

One major contribution of the discipline of economics to the water production function literature is to resolve unambiguously in a theoretical sense the issue of what constitutes an efficient or desirable level of production. The essence and purpose of economic analysis is to define the most efficient level of resource use and output levels. This is accomplished by resorting to the notion of economic efficiency, a notion that encompasses the concept of value. The efficient use of water, land, and other resources depends upon their value to the grower relative to their value to society for use in achieving other purposes. In other words, if the value created by employing a resource in crop production is greater than or equal to the value to society of utilizing the resource elsewhere, then the resource is being used efficiently. Economic efficiency, then, can be defined as follows:

> Allocation of a good or a resource is economically efficient if society cannot be made better off by shifting any amount to some other use. This implies that each increment of the good or resource goes to the highest valued use from society's standpoint.

If allocation of all resources is efficient, the value of those resources to society is maximized. If the allocation is in any way inefficient, the value to society is correspondingly reduced, and society is getting less from them than is possible. The principal difference between the notion of economic efficiency and the efficiency notions most commonly introduced in the literature on irrigation and agronomy is that the latter definitions neglect the concept of value.

The theory of production is the basis upon which most work on the economics of crop water use is founded. The brief review of that theory which follows is intended to provide a broad framework for use in understanding and interpreting the specific studies of the economics of crop water use.

The Nature of Production Functions

The theory of production is based on some general relationships that capture the way firms and industries transform inputs into outputs. These realtionships hold true so commonly that they are often stated in the form of laws. One fundamental law of production theory states that inputs may be combined in various ratios, rather than in a fixed ratio, to produce the output. This is known as the *law of variable proportions* and is fundamental to all other concepts in production theory. Although a few exceptions exist, it is clear that water input for crop production does exhibit this property: with all other inputs fixed, the application may be varied and will result in corresponding variations in yield.

It is useful to analyze the effect on output of a single input increased from zero, holding all other inputs fixed. The conventional production function in one variable appears in Figure 4(a). As input increases, three regions or stages of characteristic output response are seen. In Stage I the average output per unit (average product) is increasing, which implies that the incremental output created by the last unit of input (marginal product) is always greater than the average product, as seen in Figure 4 (b). This means that for the case of irrigation water, the water use efficiency is increasing throughout this stage, reaching a maximum at the end of Stage I.

As seen in Figure 4 (b), the marginal product begins to decline at some point in State I, and this point (A in Figure 4) may be much nearer the origin than is pictured. Throughout the range of input levels beyond *this point of diminishing returns* the marginal product is decreasing; that is, additional input contributes less and less to output. This relation holds for virtually all production functions, and is known as the *law of diminishing returns*. That this law is intuitively obvious may be seen by an example using two inputs, water and land, to produce a crop. If land is fixed and water application is increased, additional water would begin to contribute less and less to yield increases. Eventually, additional water would result in no further increase, and in fact would cause a decline in yield as the ground became waterlogged.[1/]

The second stage of production function begins at the maximum of the average product curve, where marginal product is equal to average product, and ends at the point where marginal product is equal to zero. Thus, both average and marginal products are positive and declining throughout Stage II. Stage III occurs where the marginal product is negative.

If the producer faces a constant price[2/] for both the input and the product, then throughout the range of increasing average product (Y/A), i.e., throughout Stage I, revenue per unit of input is increasing while cost per unit of input remains constant. Average revenue is calculated as ($P_Y \cdot Y/A$) which rises as average product rises, while average input cost is simply the input price, P_A, a constant. Therefore for a firm

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[1/]This law holds for any one input. It does not necessarily hold, however, for all inputs increased jointly. If all inputs are increased by a fixed percentage, output may increase by a smaller percentage (decreasing returns to scale), by the same percentage (constant returns to scale), or by a greater percentage (increasing returns to scale).

[2/]Constant refers to the price being invariant with quantity used or quantity produced. It does not mean constant over time.

facing constant prices, increasing input causes total revenue to rise faster than total cost, so profit will increase through Stage I. A competitive, profit-maximizing firm will not produce in Stage I since by so doing it foregoes additional profit. However, a monopolistic firm may under certain circumstances choose to operate in Stage I, since the price of its input or output may change with the level of production. Furthermore, it is apparent that no firm would knowingly operate in Stage III, since by cutting the level of input it could both raise revenue and reduce cost. Thus, Stage II represents the appropriate range of input for a competitive, profit-maximizing firm.

The same conclusion can be demonstrated mathematically. Let:

P_A = price of variable input, A

P_Y = price of output

FC = fixed cost

A = quantity of variable input

Y = quantity of output

MP_A = marginal product of A = $\frac{\partial Y}{\partial A}$

AP_A = average product of A = $\frac{Y}{A}$

The firm's profit function is: $\pi = P_Y \cdot Y - P_A \cdot A - FC$. The firm can increase profit as long as the additional revenue generated by another unit of input exceeds the additional cost of that unit. The additional revenue is equal to the change in output per change in input (MP_A) multiplied by the price received for a unit of output (P_Y). The additional cost is simply equal to the price of the input (P_A). From the law of diminishing returns we know that MP_A decreases as A increases while P_A and P_Y remain constant. Therefore, as input increases, the marginal revenue decreases while marginal cost remains constant, and profit will increase until the marginal revenue has dropped to the point of equality with marginal cost. It is here that profit is maximized.

Mathematically, the firm's profit function is:

4) $\pi = P_Y \cdot Y - P_A \cdot A - FC$

5) $\frac{d\pi}{dA} = P_Y \cdot \frac{\delta Y}{\delta A} - P_A = 0$

or $P_Y \cdot MP_A = P_A$

as predicted in the preceding paragraph. The revenue term in (4) can also be expressed as:

$$P_Y \cdot Y = P_Y \cdot Y \cdot \frac{A}{A} = P_Y \cdot A \cdot \frac{Y}{A} = P_Y \cdot A \cdot AP_A$$

Using this expression, and substituting from the profit-maximizing condition in (5), the firm's profit becomes:

$$\pi = P_Y \cdot A \cdot AP_A - P_Y \cdot A \cdot MP_A - FC$$

$$\pi = P_Y \cdot A(AP_A - MP_A) - FC$$

Clearly profit will be greater than or equal to zero only in the region where AP_A is greater than MP_A, i.e. Stage II of the production function. For a competitive firm, efficient production occurs in this stage.

For a perfectly competitive firm, where profit is zero:

6) $AP_A - MP_A = \frac{FC}{A \cdot P_Y}$

It is clear from equation (6) why maximizing the productivity of a variable input is inefficient. If irrigation water is the input and maximizing the water use efficiency is the professed goal, this goal is achieved at the maximum of the AP_p curve (see Figure 4(b)), where AP_p is equal to MP_p. From equation (6) it is apparent that this point is economically efficient only when the fixed cost of the other inputs is zero. This, of course, is never the case[3/]. Therefore, pursuing a goal of maximum efficiency of any input (water, labor, land) necessarily results in the other inputs being used inefficiently.

The marginal product of an input times the price of the output (the expression appearing on the left hand side of equation (5)) is called the marginal value product. It represents the value the producer will receive from the last unit of input. By setting the marginal value product equal to price of the input, the producer maximizes profit. If a farmer applies water at a level to achieve maximum yield, the marginal product of the water is zero. From equation (5) it is clear that application at the maximum yield level implies that the farmer is treating water as a free good. If the farmer knows what the production function is, and is purchasing the water through a market, maximum yield would never be the efficient level of production since it does not incorporate the value of water in other uses.

Value is implicit in the notion of economic efficiency. The market mechanism achieves efficient allocation of a resource by allowing a

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[3/] Production at this point is also inefficient, indeed nonsensical, when profit is some positive number, such that: $AP_i - MP = \pi + \frac{FC}{X_i} \cdot P_Y$. FC would have to be negative.

comparison of the value gained by the purchaser of a resource with the value given up by society by supplying that resource (in terms of other goods and services which could have been produced). Overall efficient production is achieved by employing all resource inputs based on their value as reflected in market price. Maximizing output or maximizing the efficiency (average product) of any one input fails to take account of the true value of resources.

The assumptions inherent in the preceding analysis should be reviewed. First, it is assumed that the level of technology is fixed. This is reasonable for any given time, but over time technology may change with the result that the production function shifts. Such a shift is distinct from shifts attributable to changes in the amount of the "fixed" inputs alone, because technological changes allow more output to be obtained from a given level of inputs.

A second assumption of production theory is that every unit of the variable input is identical in quantity and quality. This assumption may be widely violated in agricultural situations because of variations in water quality and other environmental factors. As a result, care must be taken to eliminate or account for such quality differences in formulating or interpreting agricultural production functions.

A third assumption of standard production theory, one which is particularly important for crop water production functions, requires that the variable input or inputs be applied in the most efficient manner. A production process may be thought of as a sequence of actions, using various combinations of inputs, which yields an output. The timing of input applications within this process has generally been treated by economists as a matter of technical efficiency and management rather than of economic analysis. The implicit argument behind this treatment is that the cost of using an input is unaffected by the stage of the production process in which it is used, and so maximum output per unit of input is the only determinant of the timing of application.

This assumption may be violated in irrigated agriculture. The optimal sequence of water application can vary from year to year based on weather variables such as relative humidity, rainfall, temperature, and wind. As a result, increasing information and managerial costs must be incurred in order to obtain the most technically efficient timing of water application. Two theoretical approaches are available for incorporating the effects of timing of application on yield into production functions. Both approaches divide the production process into stages, each of which have a unique output response to input (essentially, each stage has a production function).

The first approach, which appears in some of the crop production literature, treats the variable input in each stage as separate input. Thus, for a four-stage production process, instead of a production function in a single variable, a function in four variables is derived. Each variable would represent the water input in a particular growth stage. Each stage could have the same production function form with only the coefficients or exponents varied (see, for example, Gowon, Anderson, and Biswas, 1978). Alternatively, a separate functional form for each of the stages could be specified (see Burt and Stauber, 1971).

A second approach, which has not been explored in the crop production literature, treats the crop at the end of each growth stage as an intermediate product which is then used as an input to production in the following stage. A strictly theoretical treatment of this concept may be found in the literature on production theory (see Carlson, 1956). Essentially, production in the first stage uses water and (n) other inputs to yield the first intermediate product:

7) $Y_1 = f(W_1, X_{11}, X_{12}, \ldots .X_{1n})$.

The intermediate product is then an input in the second stage to yield a second intermediate product

8) $Y_2 = f(W_2, Y_1, X_{21}, X_{22}, \ldots .X_{2n})$.

The water and other inputs in a given stage's function are only those inputs which occur during that stage. Inputs occurring in previous stages are embodied in the form of the intermediate product.

Within this framework, only the final product (Y_4 for a four-stage process) expresses actual crop yield while intermediate products express the ability of the immature crop to respond to inputs in the next stage. The intermediate product would be a "crop state", which not only incorporates size and vigor of the plant, but embodies the ability of the crop to respond to later inputs. If a specification of the "crop state" is possible, this framework would allow the inclusion of "conditioning" (also called inter-stage dependence) to crops.

The economic literature on dated production fucntions (reviewed in a later section) does not include attempts to incorporate inter-stage dependence, although frequent mention has been made of the need to do so.

It appears that inter-stage dependence could be incorporated into either of the approaches to dated production functions, although the actual specification remains open for future research.

A final significant assumption of production theory as outlined so far allows for only one input to vary while other inputs are held constant. This assumption is particularly strong and usually must be relaxed if production situations are to be analyzed realistically since producers normally have many opportunities to combine multiple inputs in varying proportions. Growers typically manage a host of inputs, including land, labor, fertilizer, and capital in their production operations. Only if each input is totally independent of all others in its effect on yield is the "all else constant" assumption valid. In irrigated agriculture, many inputs interact with water in complex ways to affect yield. Examples of such interactions between water and other inputs include:

1) The increased osmotic tension produced by the application of fertilizer.
2) The use of capital-intensive irrigation systems to reduce the amount of applied water necessary to meet evapotranspiration.
3) The use of labor (in the form of management) to economize on water use.
4) Differences in soil types that may effect the quantity of applied water necessary to obtain some given level of yield.

The existence of such interactive effects among inputs underscores the need to exercise care when interpreting studies that assess the production implications of only one input.

Economic theory does allow for the incorporation of two or more variables into a production function. Not surprisingly, the mathematics used to describe these more comprehensive production functions becomes more complex. However, the major ideas derived for the case of a single variable input situation also apply to multiple inputs. Specifically, the law of variable proportions, the law of diminishing returns, and the efficiency of production in Stage II are equally applicable in situations involving multiple inputs. The principle additional conclusion flowing from the analysis of the multiple input case is that the marginal product of water will depend upon the quantities of other inputs used. These quantities depend, in turn, upon the prices of those other inputs.

The Problem of Risk

The production of crops is inherently a risky enterprise. Climate and other biotic factors such as pest invasions are largely beyond the control of growers. In some instance, prices paid for inputs are subject to sharp fluctuations and crop prices received are sometimes neither predictable nor stable. The result is that all growers must cope directly with a host of factors that may crucially influence their operations but which are largely outside of their control.

The production function literature surveyed in this report assumes for the most part that production functions are known with complete certainty. The simple analytics of economic production summarized in Figure 4(a) and the associated discussion assumes that production functions are known with complete certainty. If this assumption holds, it means that any farmer should know rather precisely the impact on yield of any adjustment in applied water. The assumption is contradicted, however, when the production function is not completely known as in cases where timing and interstage dependency are important. Additionally, the production function is not completely specified until the impact of other factors affecting production such as fertilizer, climate, water quality, soil characteristics and a host of others on the water-yield relationship is well understood. The result is that despite the substantial body of knowledge available on crop water relations, knowledge is not so complete that a grower can engage in moisture stressing with complete certainty as to what the results will be.

The implications of risk or uncertainty for crop water production functions have received little attention. English and Orlob (1978) investigated the problem utilizing portfolio theory. They assumed that growers respond to risk by deciding which crops to grow while recognizing that each crop has a different water use intensity. They suggest and assume that growers maximize utility which is a combination of profit and certainty rather than straight profits. Subsequently, they demonstrate, that if farmers are somewhat adverse to risk they will tend to select the cropping and (by implication) water use patterns that are less profitable but more certain than the profit-maximizing combination.

The implications of this anlaysis are important. There is little systematic literature on the preferences of growers for risk. If growers are risk averse they are likely to apply more water than absolutely necessary as insurance against the yield penalties that might accrue if they put on too little. This could mean that a grower would knowingly and rationally operate in the stage III region of the production function.

If growers are completely risk-neutral, they would then operate in stage II for the reasons elaborated upon earlier. In the absence of explicit knowledge of grower's preferences for risk, it is not possible to know what the optimal point on the production function is since that point varies with the degree of risk neutrality or risk adversity.

It is often suggested that growers have a tendency to over-irrigate because water is underpriced. A conventional conclusion of economists is that irrigation applications would be optimal if water were priced according to its true scarcity value (see, for example, Ayer, Hoyt, and Cotner, 1980). This conclusion is correct as far as it goes. It fails, however, to account for risk and the tendency of risk averse growers to use more water than absolutely necessary as a means of ensuring against both the penalties associated with underirrigating and the vagaries of his business in general. The extent and desirability of purposeful moisture stressing cannot be accurately assessed without more knowledge of the role of water in reducing (or increasing) perceived risk. The workability of moisture stressing regimes and the response of farmers to involvement to utilize them cannot be fully assessed in the absence of more knowledge on the role of risk in irrigation decision making.

Conclusions

The discussion of production theory illustrates that underpricing of a resource will lead to inefficient overuse of it. While risk-averse behavior may cause growers to apply more water than they would in the absence of risk, the conclusions with respect to pricing still hold. An increase in the price of an input (water) will cause all growers to use less of it. The extent of the reduction in water use would depend upon the degree to which each individual grower is risk-averse as well as on the particular environmental factors (such as crop type, soil, and climate) that influence his particular production operation. This analysis suggests that the failure of existing water allocating institutions to price water according to its true scarcity value is a principal cause of excessive water use in agriculture. This fact has important implications for the problem of valuing both the direct and incidental effects of agricultural water conservation.

ECONOMIC METHODS OF VALUING THE IMPACTS OF AGRICULTURAL WATER CONSERVATION

Methods for Estimating Private Costs and Benefits

Most economic methodologies rely on the assumption that price is an accurate and reliable indicator of value. In well-functioning markets, prices are determined by the interaction of factors affecting the costs of production and the willingness of users or consumers to pay for the commodity or service in question. Where markets are imperfect or fail for institutional reasons to function relatively freely, price distortions occur. In such instances, the resulting prices are not valid measures of the value of the good or service in question. As a consequence, the first problem to be overcome in any effort to assess the direct value of water as well as the value of impacts incidental to the use of water is one of estimating the correct price.

A number of methods have been devised for use in inferring the price of water that would obtain if it were traded in well functioning markets. These methods are based on the concept of derived demand. The demand for water or willingness of a user to pay for it is derived from the demand for the product (agricultural produce) that it produces. The derived demand schedule can be identified by computing the value marginal product of water at different levels of application. The value of the marginal product is simply the marginal physical product of water multiplied by the market price of the product which it is used to produce. Since agricultural commodities are traded in well functioning markets, the derived demand for water can be computed from a crop-water production function and the price of the crop in question.

Hexem and Heady (1978) utilized empirical data from field experiments in seven western states to estimate statistically the water-yield response relationship for a variety of field crops. Although the procedure used to estimate these relationships ignored the timing of the application of irrigation water, the resulting production functions provide a reasonable approximation of the true relationship. These production fucntions were subsequently used in a linear prcgramming model to estimate the derived demand for water. A number of other investigators have used linear programming techniques to estimate the value of water in California (see, for example: Moore and King, 1961).

Howitt et al. (1980) demonstrated that a quadratic programming approach removes systematic biases in linear programming attributable to the requirement that all functional relationships used in the latter method must be linear. Howitt et al. showed that the use of water is more responsive to price than had previously been thought. These results imply that the price of water in agriculture is somewhat higher than previously assumed. Adams et al (1977) used a quadratic programming format to estimate the implications for on-farm energy consumption of water use in northern California. The specific water prices which they estimated agreed quite closely with the more generalized price estimates of Howitt et al.

A recent study by Howitt, Mann and Vaux (1981) simulated regional water markets in an effort to determine the price of water that would be generated if limited water trading were permitted. They estimated regional supply and demand functions for water in California and subsequently utilized these functions in an interregional programming model to generate estimates of equilibrium prices. The price estimates that were generated agreed reasonably well with those estimated through quadratic programming. All of these estimates are aggregative and make no allowance for variations in cropping patterns on the range of localized agricultural conditions.

Derived demands can be used to estimate the savings to growers (private benefits) from agricultural water conservation. Since the true price of water is higher than the actual price, the marginal physical product of the last unit used is currently lower than it would be if prices reflected true scarcity value. The savings to growers would thus be the difference in the value marginal products attributable to the underpricing of water. These values will differ among crops and vary with local growing conditions. Although this methodology is well developed and well-known, its use in estimating the on-farm effects of agricultural water conservation is constrained by a lack of available data.

Accurate formulations of water-yield production relationships are required to estimate marginal physical products for different crops grown in different locations. Vaux et al. (1981) suggest that current knowledge of these relationships is not general enough to permit precise calculations of marginal physical products. Additionally, the problem of accounting for risk in such computations is essentially unresolved. As a consequence, while it may be possible to develop some approximate aggregative estimates of the direct savings to growers, there is insufficient information to permit evaluation of such benefits on a local basis. It should also be noted that the costs of generating this information may be quite high.

Applications of derived demand usually require the analyst to ignore one or more of the variables to which on-farm water use is crucially linked. There are a number of studies which examine the economic relationships between these variables explicitly. A methodology common to many such studies is the farm budget analysis or partial budget analysis. This method requires the analyst to estimate farm revenues and expenditures and the changes in them under a variety of circumstances. Such estimation can be done either directly through the use questionnaires or farm cost analyses or statistically for some idealized average farm. Wilson et al. (1976) utilize this technique to estimate the on-farm savings of converting from surface irrigation methods to drip and sprinkler irrigation for citrus in Arizona. Although their analysis is only partial, it demonstrates that the benefits and costs associated with increases and declines in complimentary and substitute inputs can be identified.

A reasonable data base for use in farm budget analyses is available through the California Cooperative Extension which has developed a series of sample production budgets for different crops. These budgets are updated periodically. They are generally developed through direct estimation procedures. However, these data may be of limited usefulness in assessing the costs and benefit of radical changes in farm water use since they reflect current water use prices and practices and are not based on any generalized relationships between farm inputs. The result is that budget studies can be used to estimate very small changes quite reliably but are likely to yield sizeable errors for situations in which sharp changes in water availability and prices might alter fundamentally the techniques used to farm.

If input factor proportions are fixed, the implications of water savings for the complimentary factor can be estimated directly. The study of Moore (1981) estimates the cost of energy required to pump groundwater and demonstrates how energy cost savings associated with a reduction in groundwater use could be computed. The computations require information on the pumping depth and efficiency of the pumping plant. The work of Roberts and Hagan (1976) provides estimates of the amount of energy needed to move water through various federal, state and local conveyance systems in California. Their figures could be used in conjunction with prevalent energy rate schedules to compute the money savings to growers associated with a reduction in the water applied from those systems. It should be noted, however, that energy rate schedules do not always accurately reflect the marginal cost of energy and adjustments in power prices may have to be made depending upon the basis of the rate schedule that applies.

The work of Letey et al. (1977) suggests that in practice there may be a fixed proportional relationship between fertilizer and water applications. Further work is underway in an effort to confirm this conclusion. If confirmed, it will be possible to estimate directly the savings in fertilize cost associated with reduced water applications.

The relationship between water and other inputs to farm production appears to vary substantially both with the scale of farm operation and with environmental conditions. The studies of these relationships cited earlier in this report are quite specific, and, for the most part, generalized relationships have not been identified. As a result, it is not possible to generalize about the relationships between water and other inputs. Direct costing techniques will thus have limited applicability until such time as these relationships are more comprehensively understood.

The methods available for estimating the private costs and benefits associated with agricultural water conservation are well developed and conceptually sound. Their applicability is limited largely by the lack of comprehensive data on the various impacts associated with changes in the level of on-farm water use. Finally, it should be reemphasized that private costs will be accounted for by a grower in making his irrigation decisions inasmuch as those costs are a direct consequence of the decision. Growers have an incentive to be knowledgeable about such costs since they directly effect the profitability of the growing operation. In short, it is likely that each grower is thoroughly knowledeable about the factors that influence his costs. Aside from existing information disseminating activities such as those carried out by Cooperative Extension there is probably little use to be served by large scale public programs intended to acquaint growers with the costs of agricultural production.

Methods for Estimating External Costs and Benefits

Methods for estimating external technological costs and benefits are fairly well developed from a theoretical and conceptual standpoint. The availability of empirical data largely limits their applicability. However, the general methods for estimating external technological costs and benefits have been discussed by a large number of investigations including Baumol and Oates (1977), Baumol and Oates (1980), Haveman, Freeman and Kneese (1971), and Freeman (1978). The conventional means for estimating the value of external effects is to identify the benefit function or damage function associated with the effect. Such a function can provide a measure of the total damages or benefits of the effect. When analyzed in conjunction with functions expressing the costs of controlling the effect, it provides information as to the optimal level of control. This latter point is important.

A number of authors, beginning with Buchanan and Stubblebine (1962), have pointed out that there is some optimal level of external effects. Simply stated, this means that only where the costs of controlling the externality are zero or where the damages associated with it are infinitely high, will it be economically efficient to eliminate the externality altogether. In other words, in usual circumstances a point is reached at which the costs of controlling the externality exceed the benefits from controlling it. Accordingly, beyond that point it is less expensive to suffer the consequences of the externality than to control it further. In these instances, the remaining damages and costs are optimal. Thus, it is usually improper to assume that the total benefits or damages from an externality are equivalent to the total value of that externality. In order to obtain an accurate estimate of total value it is necessary to know both the costs of control and the benefits (or damages avoided) by control.

The principal external effect of agricultural water use that has been analyzed by economists is salinity. A number of studies of the impact of salinity on agriculture in the Colorado Basin are illustrative of the techniques available for estimating the economic impact of off-farm effects of agricultural water conservation. Moore, Snyder and Sun (1974) utilized a linear programming model of agriculture in the Imperial Valley to estimate the damages associated with various levels of salination in Colorado River water. Kleinman and Brown (1980) utilize a large linear programming model to estimate salinity damages throughout the entire lower Colorado Basin. Martin and Booster (1976) use a simple opportunity costing technique to arrive at conclusions relative to the least cost means of controlling the contribution of irrigation in the Wellton Mohawk District to salinity levels in the lower Colorado. Skogerboe, Walker and Evans (1977) use direct costing techniques to estimate some costs of controlling salt emissions from the Grand Valley in the upper Colorado Basin.

A primary reason for the success in estimating the economic impacts of salinity stems from the rich scientific data base on salinity. Kinney, Horner and Tanji (1977) demonstrate how models of salt transport in soil systems can be linked with economic models in order to develop estimates of damages and control costs associated with various levels of reduction in salt emissions. Similar success has been realized in estimating the implications of alternative rates of exploitation on groundwater pumping levels.

Burt (1962), Cummings (1972), Howitt (1977), Noel, Gardner and Moore (1980), and Gisser and Sanchez (1980), are but a few who have modelled the dynamic processes of groundwater recharge and exploitation and developed estimates of net savings or costs associated with alternative groundwater pumping levels. These models are all basin specific and the accuracy of the results which they produce is dependent on the level and accuracy of knowledge of the physical and hydrologic parameters that govern the behavior of aquifers. Although most of these authors report their results in the context of values to be realized from groundwater management, it would be relatively simple to adapt the methodologies and assess the implications for groundwater levels of a decline in the rates of pumping and variations in the rate of recharge due to diminished applications of irrigation waters.

Helweg and Gardner (1978) look broadly at the economic implications of irrigation for groundwater quality. Cummings (1974) examines empirically the groundwater quality implications of excessive rates of pumping in northern Mexico. His work demonstrates that the principal problem associated with the economic evaluation of changes in groundwater quality is the identification and specification of variables that determine water quality. Cummings' work does suggest, however, that it is possible to estimate the economic impact of improvements or declines in quality where the relationships between irrigated agriculture and groundwater quality are known.

Studies on the remainder of the incidental external technological effects of agricultural water conservation identified in this report are lacking. General studies on the topics of pest control (Langhorn et al., 1972) toxicity (Page, 1980), and wildlife (Hammock and Brown, 1974) are not specifically focused on the role of water in producing beneficial or adverse effects. They do, however, provide methodological guidance for the estimation of the external econnomic impact of water on the various incidental effects identified in this report. The principal information required to carry out such studies are data on the relationship between water use in agriculture and pest control, toxicity, and wildlife, respectively.

Most studies of external technological effects are carried out under the general rubric of benefit-cost analysis. Benefit-cost analysis was pioneered in the middle 1930's and, although it has been subject to abuses by many government agencies, the techniques are reasonably well developed. A useful survey of the conceptual underpinnings of this type of analysis has been written by Mishan (1970). A series of critiques on both the conceptual and empirical problems of applying benefit-cost analysis is contained in the work of Seskin and Peskin (1973). This latter work deals exclusively with the application of benefit-cost analysis to the valuation of water quality. The work underscores the fact that benefit-cost analyses are information intensive and the quality of the results is directly related to the adequacy of available information.

Sound techniques are available for measuring the economic magnitudes of virtually all classes of incidental external (off-farm) effects associated with agricultural water conservation. These methods currently have limited applicability, however, because of the sparseness of scientific data characterizing the effects of agricultural water conservation. Existing work on the economic magnitudes of damages associated with increasing salinity of irrigation water suggests that where the physical and biological roles of water in producing external effects are well understood, measures of economic magnitues of damages and benefits can be developed in straightforward ways.

The assessment of pecuniary externalities is also information intensive and is fraught with complexity. To assess the change in prices which may be associated with changes in the levels of water use it is necessary to develop a model which characterizes the whole range of economic activities in a region or state. Various types of simulation models have been constructed using econometric (statistical) techniques to estimate the relationships between various economic sectors in a region. Such models require a great deal of data about the past economic activities of the region. Additionally, since they reflect the economic history of a region they are only accurate predictors of future price changes when historical relationships prove an accurate guide to the future.

Input-output analysis is often used to examine the effects of economic changes on prices, outputs, and employment in a region. In this type of analysis, it is necessary to know rather specifically how each industry is related to the other in the form of an input-output coefficient. Such coefficients can be estimated with reasonable accuracy for very large regions. As the region of focus becomes smaller, it is more and more difficult to estimate the coefficients accurately. Additionally, input-output analysis requires the use of several very strong assumptions which may constrain the accuracy of results generated with it. Economies of scale cannot be accommodated, and it is assumed that all factors of production are combined in fixed and unvarying proportions. Subject to these limitations, input-output analysis does provide a means of estimating the pecuniary effects of agricultural water conservation.

To date, there are no studies focusing exclusively on the pecuniary effects of agricultural water conservation. Methodologically these effects are likely to be more difficult to assess than either the private costs and benefits or the external technological costs and benefits.

ADEQUACY OF AVAILABLE INFORMATION AND NEED FOR FURTHER STUDIES

ADEQUACY:

WATER CONSERVATION AND INCIDENTAL EFFECTS

As was pointed out in the "Bibliography of Incidental Effects" there is really no information in the literature that assesses these effects. This is not surprising since: 1) the effects of a large variety of agricultural water conservation actions must be assessed; 2) the subject is extremely broad (we identified over 400 incidental effects, grouped into 23 categories); 3) an in-depth analysis is required since both the benefits and costs must be assessed; 4) the effects can be crop- and site-specific; and 5) we must be concerned not only with on-farm, but also with off-farm effects.

The starting point of such an assessment must begin with the water conservation actions that cause the incidental effects. There is a large body of information on various techniques for conserving water in both rain-fed and irrigated agriculture, but it should be understood that the desirability of any conservation action, even if considered only for the purpose of saving a quantity of water, must be determined in the context of: 1) the "need" to conserve water (scarcity, cost, etc.); 2) the applicability of the conservation technique in relation to climate, soil and crop conditions; and 3) the economic efficiency of the conservation action (cost of action vs. value of water saved). Because of the site-specificity of such evaluations and the ever-changing costs of water and conservation related factors, analyses would need to be made for individual cases. However, information is available on most input quantities and costs, e.g., pumping energy, concrete lining of canals, land levelling, irrigation systems, etc.

The adequacy of available information on incidental effects (effects other than the saving of a quantity of water) of agricultural water conservation seems to be restricted to the information provided in this report, and this is basically an *identification* of a variety of incidental effects. As pointed out in our Bibliography, most of the literature surveyed contains information that is *pertinent* to incidental effects, but not specifically aimed at assessing the impact of agricultural water conservation actions on incidental effects (benefits and costs).

Some quantification of effects of water management actions (which may or may not be aimed at water conservation) can be found in the literature. However, care must be taken in extending the quantities reported to other sites and conditions because: 1) there are variations from year to year and from farm to farm in the degree of inefficiency of existing irrigation systems; 2) the intensity of the water conservation action is not always reproducible; and 3) an incidental effect can vary with crop and site conditions. Thus, for example, leaching losses of nitrogen from the root zone can vary from 0 to nearly 100 lb. N/ac/year, depending on management and rainfall. Also, the contribution of nitrates to degradation of the quality of receiving waters, because of low irrigation efficiencies, depends on whether or not anaerobic conditions (e.g., near high water tables or tile drains) are present to convert NO_3 to gaseous N_2. As another example, we pointed out in the CROP RESPONSES categories, that crop growth and economic yield can vary with the severity and timing of water stress (if deficit irrigation is the conservation action) and with the quality (TDS and specific ion effects) of the irrigation water (if wastewater reuse is the conservation action). Therefore, although incidental effects can be identified, there is inadequate quantitative information on all (or even the more important) incidental effects which would enable proper evaluation of effects and enable extension of the results to a variety of crops and sites. Research should continue to develop basic relationships which can be applied to estimate effects of water conservation on given incidental effects under a range of site conditons. Such information can provide input for regional models.

ECONOMIC EVALUATION OF INCIDENTAL EFFECTS

Well developed economic methods are available for assessing the costs and benefits associated with the incidental effects of agricultural water conservation. The theory and techniques for estimating private costs and benefits are well known and have been applied to a wide array of problems. They can be readily utilized to measure the effects of on-farm agricultural water conservation so long as the true price or scarcity value of water is known. Preliminary work suggests that the true price of water can be inferred for generalized regions and sectors. Further studies to confirm this finding and identify prices for more localized situations can be carried out. Aggregative analyses can be accomplished for modest cost while more detailed studies would be costly and time consuming.

The methods for estimating the technological costs and benefits of agricultural water conservation are similarly well-developed. Theoretical and econometric techniques have been used to assess a wide variety of externalities. The studies of the external costs imposed by increasing salinity of irrigation water are illustrative. Many of the effects identified in this report are not especially well understood from a scientific standpoint. However, the relative paucity of data characterizing the impact of agricultural water use on fish and wildlife habitat, certain pest problems, and air quality, for example, serve to limit the accuracy of efforts to value these effects. In short, the economic methodologies for evaluating external technological effects appear adequate, but in many instances they cannot be applied effectively because of an inadequate data base.

There are a number of economic methodologies which could be adapted for assessing the pecuniary or price implications of agricultural water conservation practices. These included input-output analyses and a variety of other techniques for modelling the economies of regions. Such models are information-intensive.

In most instances, use of them for this purpose would require the gathering of a sizeable amount of primary data, probably at considerable cost. Additionally, such models tend to predict future events accurately only when historical experience is an appropriate guide to the future. However, the methods of estimating pecuniary externalities are reasonably well-developed and there are no unique or fundamental methodological problems that would have to be overcome.

NEED FOR FURTHER STUDIES:

Because of: 1) the numerous incidental effects identifed; 2) the crop and site-specific nature of quantitative data on incidental effects; and 3) an inadequate data base for many of the varied effects, particularly off-farm impacts, it becomes difficult to determine priorities for further studies. Empirical research on the magnitudes and benefits and costs associated with water use provides some useful information, but there is a strong need for a more scientific and theory-based undertaking to permit quantifiable evaluations to be made.

The degree of variability in climate, soils, crops, the price and source of water, etc., from site to site suggests that if the impact of specific agricultural water conservation actions on specific incidental effects, both on- and off-farm is to be fully understood, it will be necessary to abstract from many variables and much of the variability. Preliminary studies assessing the potential of abstract models to depict meaningfully the impacts of agricultural water conservation could be worthwhile if acquisition of accurate data on all incidental effects becomes a public goal.

On-farm incidental effects of conserving agricultural water that are deemed important to farmers are those which have greatest impact on net revenues, and as such these (e.g., crop yield and production inputs such as energy, fertilizer, labor) are already well recognized by most growers who are in the *business* of farming. However, some effort, possibly through publicity and educational programs is needed to increase awareness of agricultural water conservation actions which have unseen and/or long term effects, particularly if those effects are off-farm and therefore are of little economic concern to those who initiate the conservation action.

Since the actual implementation of agricultural water conservation by water users and distributors is tied closely to the profit incentive, the price of water (and its proportion of the total cost of crop production) is obviously an important factor in determining incentives to conserve it. It is, therefore, important that studies be continued to determine how institutional modifications can be made to permit water to be priced and traded so as to more closely reflect its true scarcity values. If water prices more closely reflect the open market value of agricultural water, conservation is more likely to become a reality and only then will the incidental effects identified in this report receive greater recognition by those who initiate actions to conserve agricultural water.

CONCLUSIONS

Programs and policies that are designed to reduce the application of water in agriculture may have a number of side effects. Some of these incidental effects are obvious and widely recognized while others are indirect or even hidden. This report has focused on these incidental effects of agricultural water conservation. Its principal contribution is the identification of a wide array of impacts that are incidental to reductions in agricultural water use. In addition, the report contains an assessment of the likely qualitative impacts of these effects. The availability of data and methods for obtaining quantitative estimates of the effects are also discussed. The conclusions of the report fall into six categories as follows:

1. There are many effects incidental to agricultural water conservation. These effects are highly diverse, some beneficial, some costly, and some more important than others, depending on the nature and severity of the conservation action and on crop and site conditions. Most irrigation conservation impacts occur on-farm, but a substantial number of impacts are to off-farm areas and interests. The sheer number of effects (over 400 identified in this report), suggests that the impacts of agricultural water conservation are multiple, complex, and not always obvious.

2. The knowledge and understanding of most *on-farm effects* is reasonably adequate. These effects include the impacts of changes in levels of applied and consumed water on crop yield, energy, fertilizers and soil nutrients, labor, some crop pests, production costs, and soils. This knowledge permits these effects to be characterized rather precisely in terms of whether they are likely to be costly or beneficial. These effects are well understood primarily because they determine, in part, the overall profitability of a grower's operation. As a consequence, the individual grower has an incentive

to be knowledgeable about them and to react appropriately to them. Economic methodologies for assessing the quantitative implication of these effects are well developed and data are generally available.

3. The knowledge and understanding of most *off-farm effects* do not appear adequate to allow any precise characterization of the direction and magnitude of their ultimate impacts. These effects include air quality, drainage, some pest and weed population problems, toxic substances and residues, water quality, and wildlife. The implications of increasing salinity of irrigation water are understood, and they have been well characterized in the literature. Individual growers have little incentive to account for all such external effects because they do not bear directly on the short term profitability of their operations. The economic methodologies for assessing the quantitative impacts of such effects are well developed and have broad applicability. Their use in evaluating these impacts is constrained, however, by the site specificity of data characterizing the relationships between water use and off-farm effects. An accurate economic valuation of these effects will require a more comprehensive understanding than currently exists of the relationships between on-farm water use and off-farm impacts.

4. Incidental effects resulting from reductions in recoverable losses fall into a variety of categories, some of which are of direct concern to the farmer and others which are of concern off the farm. In terms of water quantity savings, farmers will usually benefit from reducing recoverable losses. Incidental effects resulting from reductions in irrecoverable losses usually involve: 1) a curtailment in crop yield (if transpiration is reduced) but may include some savings in production costs; and 2) impacts on the quantity and quality of water available for instream uses. In terms of water quantity savings, both the individual farmer and water users in the aggregate would benefit from reductions in irrecoverable losses.

5. A critical review of knowledge on the incidental effects of agricultural water conservation suggests that it is premature to develop guidelines for the evaluation of such effects. The scientific knowledge of many of these effects tends to be site specific and somewhat sketchy. As a consequence, there is very little basis from which to generalize about the likely multiple and complex impacts of agricultural water conservation and the appropriate means for measuring them. While economic methods for assessing the costs and benefits of such effects are reasonably well developed, an adequate data base required to carry out pertinent economic evaluations is unavailable. Moreover, most of the external or off-farm effects have not been characterized with enough generality to permit sound conclusions to be drawn as to which economic methodologies are most appropriate for analyzing specific effects under widely varying circumstances.

6. The information in this report suggests two approaches which may contribute to agricultural water conservation:

a. The dissemination of information to growers about the incidental effects of agricultural water conservation may hold some promise. It should be understood, however, that growers are generally quite knowledgeable about any impact which affects their costs or revenues. Care should be taken to ensure that "information dissemination" does not serve simply to reemphasize the obvious, particularly with respect to well-known on-farm effects. At the same time, dissemination of information about the nature of external (off-farm) effects is not likely to produce any change by itself. Since growers have little or no incentive to account for such effects, additional knowledge about them may not by itself foster any change.

b. Economic studies have shown that pricing of water according to its true scarcity value and the development of opportunities (even if somewhat limited) for water trading can provide a key incentive to conserve. Based on those studies, pricing reforms which tend to promote more economically efficient on-farm water use could: 1) enable realization of the on-farm benefits of agricultural water conservation, and 2) reduce some costly external off-farm effects, but may not always reduce net state-wide water demand. Reduced water use would not necessarily be optimal but would represent an improvement in the economic efficiency with which water is used.

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